BERKELEY LAB Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY

The ABC's of Nuclear Science*

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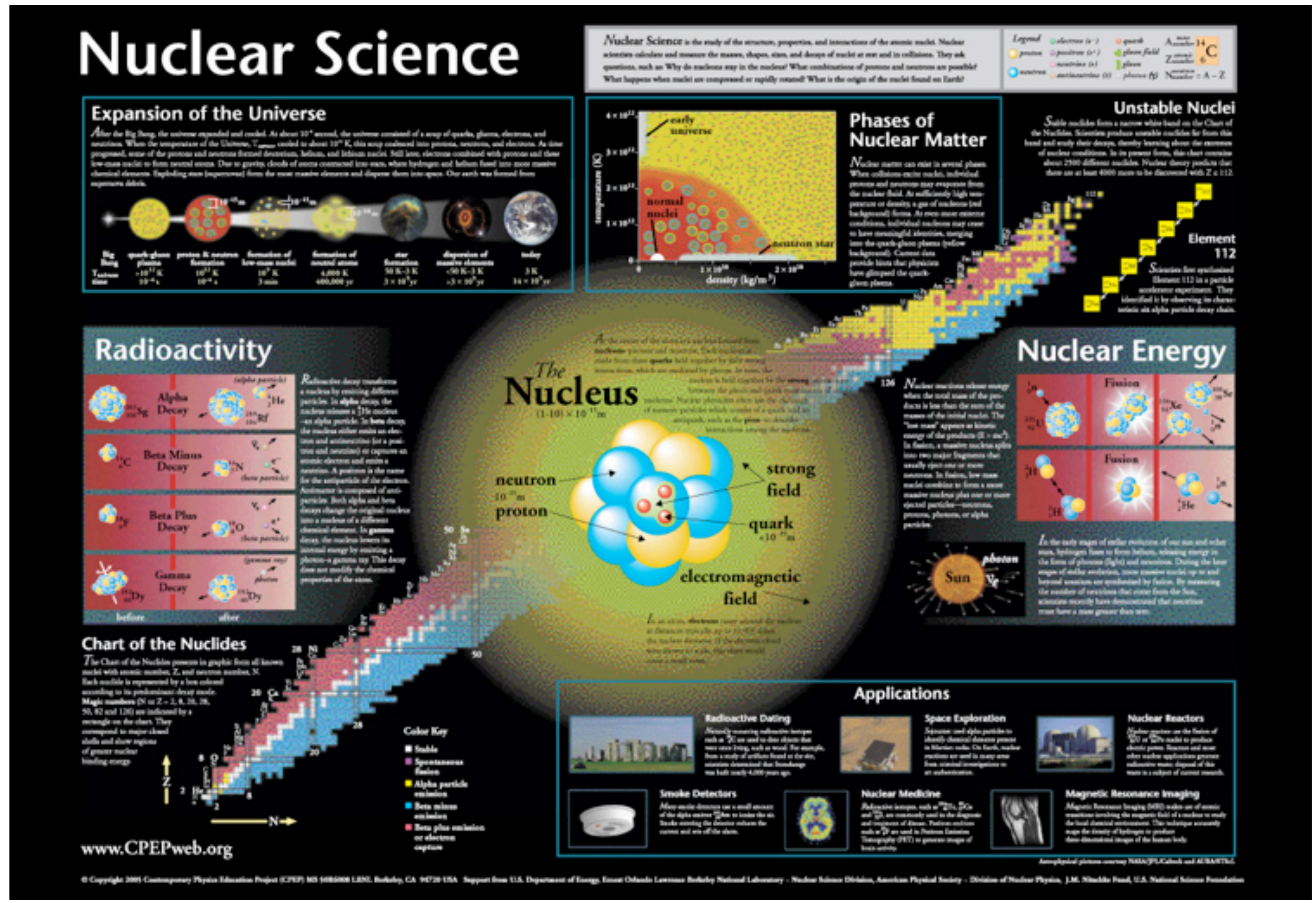
http://neutrino.lbl.gov

* Slides adapted from Rick Norman's previous talks in this workshop series

Outline

- A brief history of the nucleus
- A walk around the Nuclear Science wall chart
- Resources



http://www.lbl.gov/abc

The classical elements

Greek

Earth

Air

Fire

Water

\+ Aether (Quintessence)

The classical elements

Earth

Air

Fire

Water

Greek

+ Aether (Quintessence)

Buddhism

Hinduism

The classical elements

Earth

Air

Fire

Water

+

Aether
(Quintessence)

+

Salt

Sulfur

Mercury

Medieval Alchemy

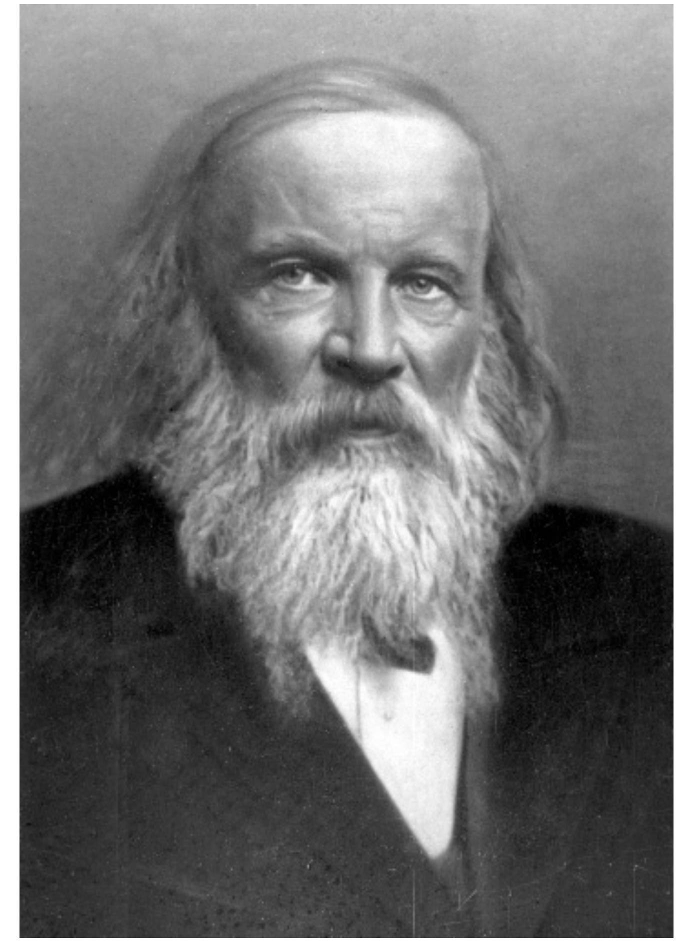
Mendeleev's Periodic Table

ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,4.
			Fe=56	Rn=104,4	Ir=198.
			Ni=Co=59	Pl=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be=9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,4	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
		Ca=40	Sr=87,6	Ba=137	Pb=207.
		?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

Д. Менделѣевъ



Dmitri Mendeleev
(1834-1907)

I saw in a dream a table where all the elements fell into place as required. Awakening, I immediately wrote it down on a piece of paper. Only in one place did a correction later appear necessary.

-Dmitri Mendeleev, 1869

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Periodic Table of the Elements

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

Key: atomic number 14 — atomic weight 28.09 — symbol: Si — name: Silicon

black solid, blue liquid, red gas, white synthetically prepared (most stable isotope)

Legend: alkali metals; alkaline earth metals; transitional metals; other metals; nonmetals; noble gases

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H 1.01 Hydrogen																	2 He 4.003 Helium
3 Li 6.94 Lithium	4 Be 9.01 Beryllium											5 B 10.81 Boron	6 C 12.01 Carbon	7 N 14.01 Nitrogen	8 O 15.999 Oxygen	9 F 18.998 Fluorine	10 Ne 20.18 Neon
11 Na 22.99 Sodium	12 Mg 24.31 Magnesium											13 Al 26.98 Aluminum	14 Si 28.09 Silicon	15 P 30.97 Phosphorus	16 S 32.06 Sulfur	17 Cl 35.45 Chlorine	18 Ar 39.95 Argon
19 K 39.10 Potassium	20 Ca 40.08 Calcium	21 Sc 44.96 Scandium	22 Ti 47.90 Titanium	23 V 50.94 Vanadium	24 Cr 51.996 Chromium	25 Mn 54.94 Manganese	26 Fe 55.85 Iron	27 Co 58.93 Cobalt	28 Ni 58.70 Nickel	29 Cu 63.55 Copper	30 Zn 65.37 Zinc	31 Ga 69.72 Gallium	32 Ge 72.59 Germanium	33 As 74.92 Arsenic	34 Se 78.96 Selenium	35 Br 79.90 Bromine	36 Kr 83.80 Krypton
37 Rb 85.47 Rubidium	38 Sr 87.62 Strontium	39 Y 88.91 Yttrium	40 Zr 91.22 Zirconium	41 Nb 92.91 Niobium	42 Mo 95.94 Molybdenum	43 Tc (98) Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.91 Rhodium	46 Pd 106.40 Palladium	47 Ag 107.87 Silver	48 Cd 112.41 Cadmium	49 In 114.82 Indium	50 Sn 118.69 Tin	51 Sb 121.75 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.30 Xenon
55 Cs 132.91 Cesium	56 Ba 137.33 Barium	57 La 138.91 Lanthanum	72 Hf 178.49 Hafnium	73 Ta 180.95 Tantalum	74 W 183.85 Tungsten	75 Re 186.21 Rhenium	76 Os 190.20 Osmium	77 Ir 192.22 Iridium	78 Pt 195.09 Platinum	79 Au 196.97 Gold	80 Hg 200.59 Mercury	81 Tl 204.37 Thallium	82 Pb 207.19 Lead	83 Bi 208.98 Bismuth	84 Po (209) Polonium	85 At (210) Astatine	86 Rn (222) Radon
87 Fr (223) Francium	88 Ra 226.03 Radium	89 Ac 227.03 Actinium	104 Rf (261) Rutherfordium	105 Ha (262) Hahnium	106 Sg (266) Seaborgium	107 Bh (262) Bohrium	108 Hs (265) Hassium	109 Mt (266) Meitnerium	110 (271)	111 (272)	112 (277)	(113)	114 (285)	(115)	116 (289)	(117)	118 (293)

Series														
Lanthanide series	58 Ce 140.12 Cerium	59 Pr 140.91 Praseodymium	60 Nd 144.24 Neodymium	61 Pm (145) Promethium	62 Sm 150.40 Samarium	63 Eu 151.96 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.93 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.93 Holmium	68 Er 167.26 Erbium	69 Tm 168.93 Thulium	70 Yb 173.04 Ytterbium	71 Lu 174.97 Lutetium
Actinide series	90 Th 232.04 Thorium	91 Pa 231.04 Protactinium	92 U 238.03 Uranium	93 Np 237.05 Neptunium	94 Pu (244) Plutonium	95 Am (243) Americium	96 Cm (247) Curium	97 Bk (247) Berkelium	98 Cf (251) Californium	99 Es (252) Einsteinium	100 Fm (257) Fermium	101 Md (260) Mendelevium	102 No (259) Nobelium	103 Lr (262) Lawrencium

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Viewing the periodic table with x-rays

- Elements are distinguished by the atomic number, Z, which is the number of protons in its nucleus → also determines the number of electrons (charge neutrality).
- Wilhelm Röntgen discovered x-rays from cathode-ray tubes in 1895.
- Charles Glover Barkla discovered that each element has its own characteristic x-ray spectrum.
- Henry Moseley established that Z is related to the frequency of the x-ray:

$$Z \propto \sqrt{f}$$

Hand mit Ringen : First "medical" X-ray

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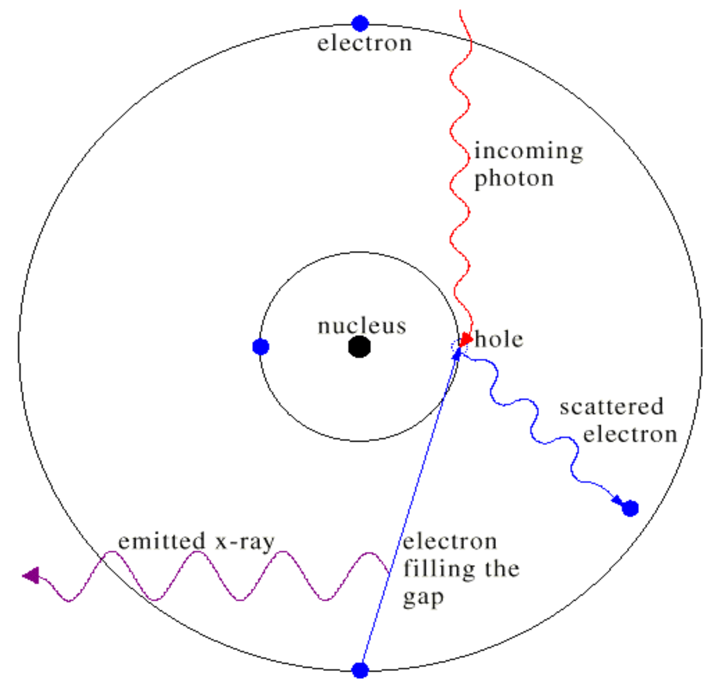

X-ray fluorescence

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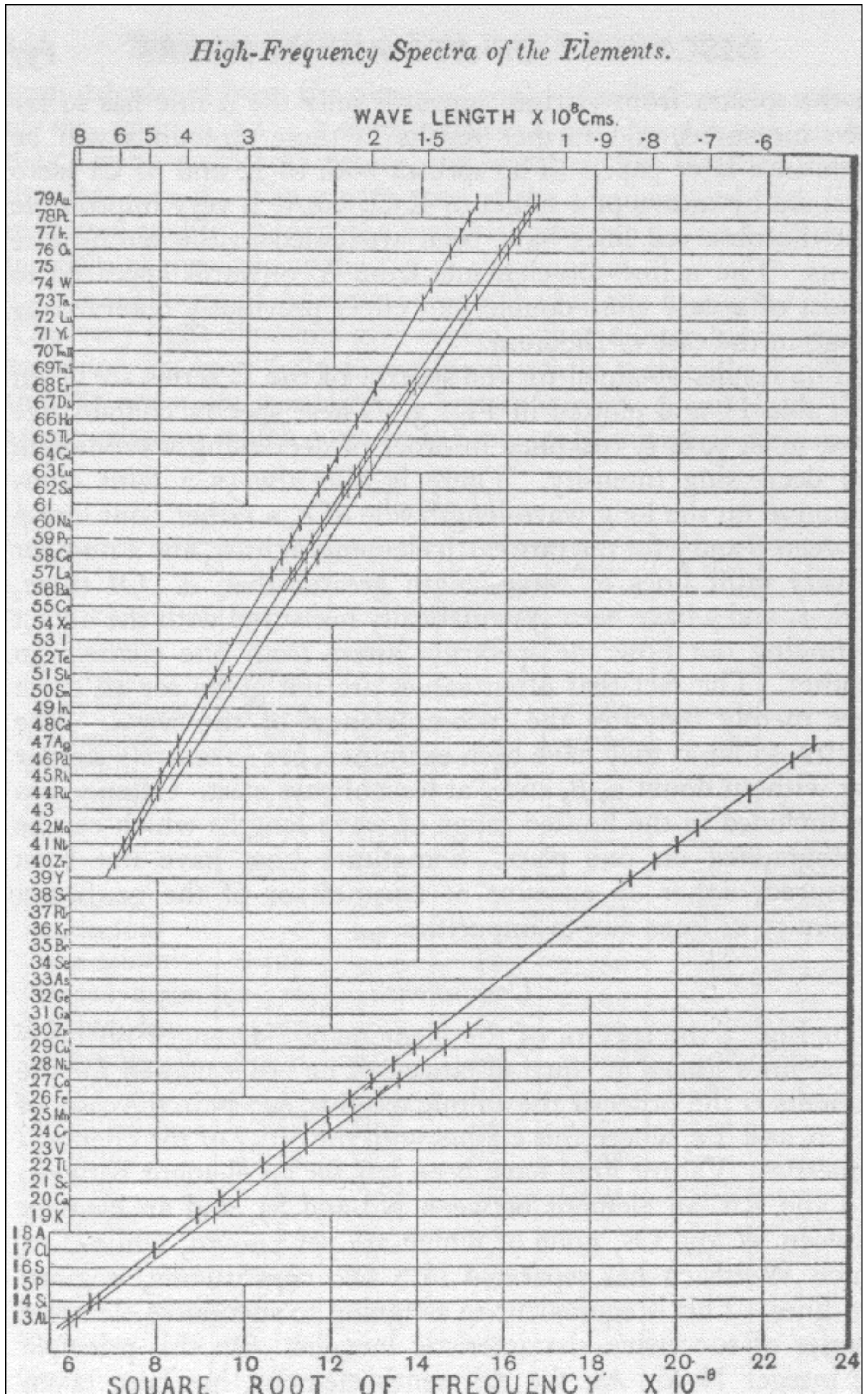

Fig. 3.

A student XRF project at LBNL

http://ie.lbl.gov/xray

A student XRF project at LBNL

^{241}Am source
E_{γ} = 59.5 keV

http://ie.lbl.gov/xray

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A student XRF project at LBNL

Sample

^{241}Am source
E_γ = 59.5 keV

http://ie.lbl.gov/xray

A student XRF project at LBNL

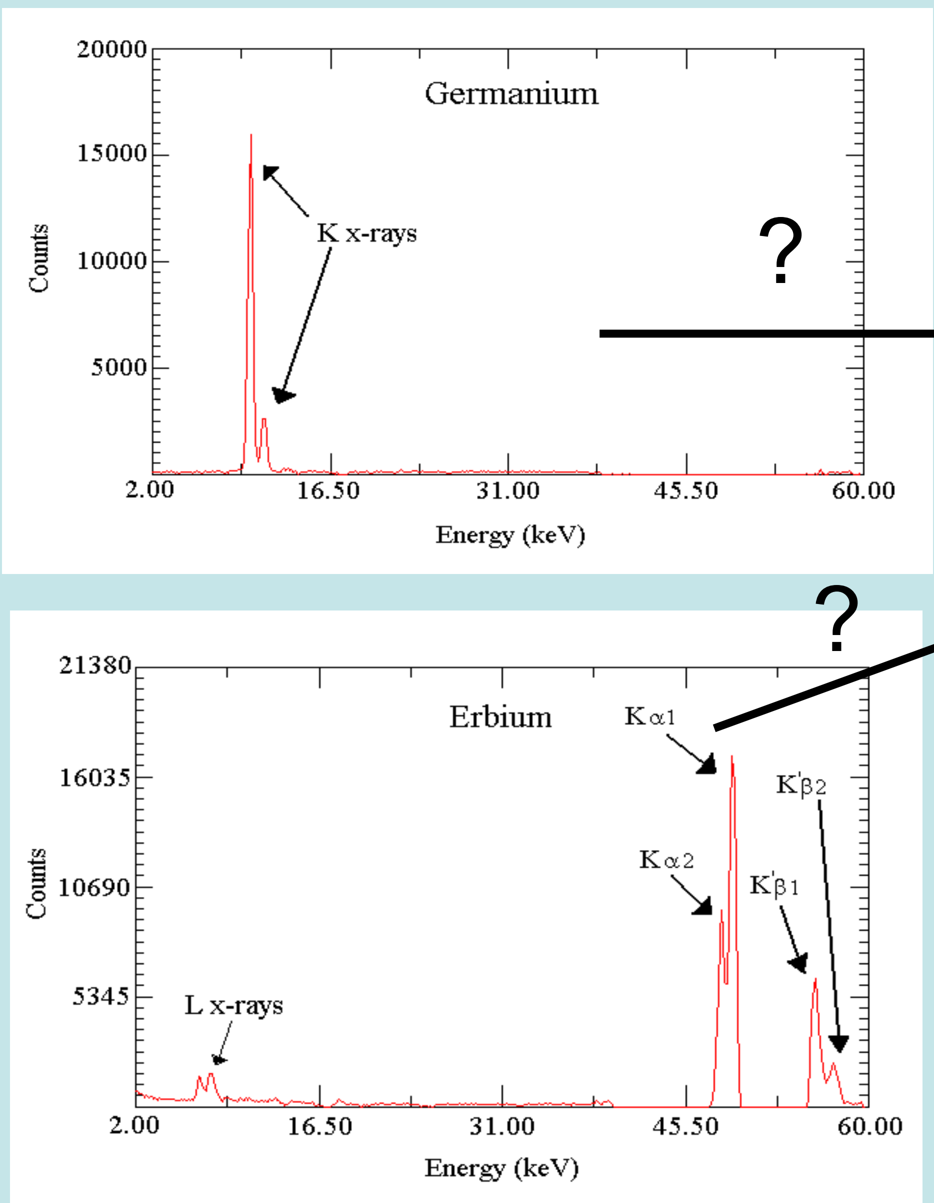
Germanium detector

Sample

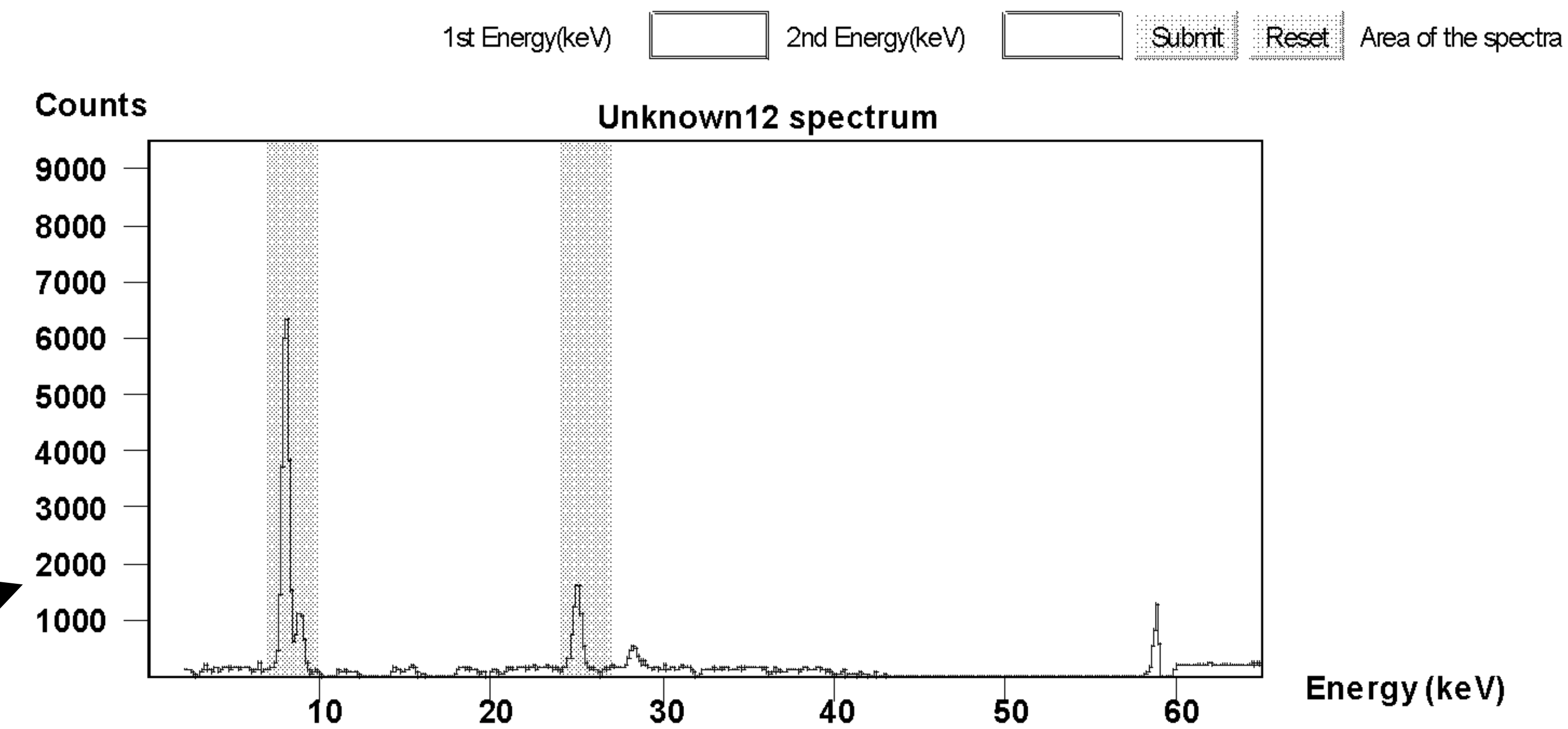
^{241}Am source
E_γ = 59.5 keV

http://ie.lbl.gov/xray

Examples of x-ray spectra available



Library of elemental x-ray spectra



- Fluorescence spectrum of the sample can be “unfolded” to find out its elemental make-up.
- XRF is a commonly used technique in many fields

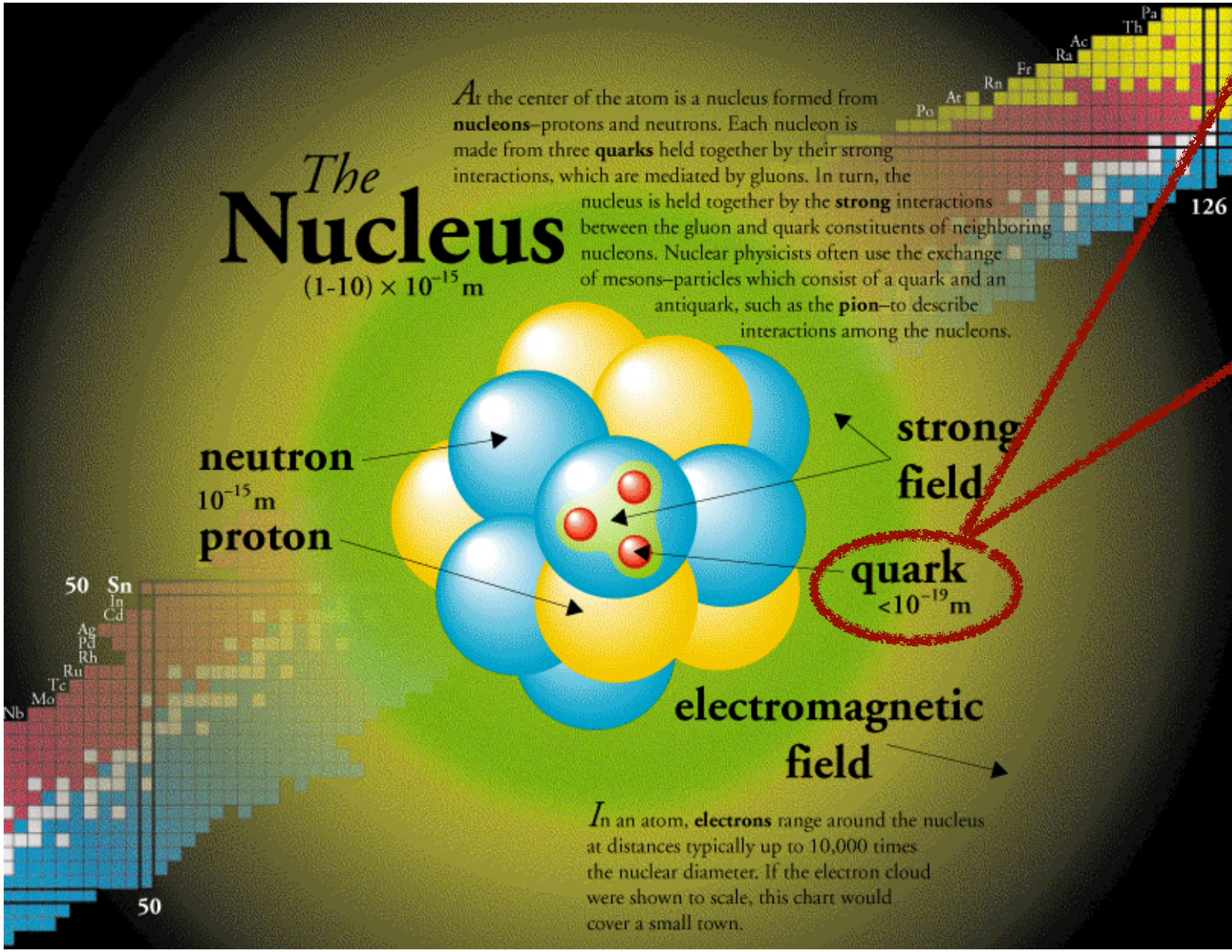
The beginning of Nuclear Science

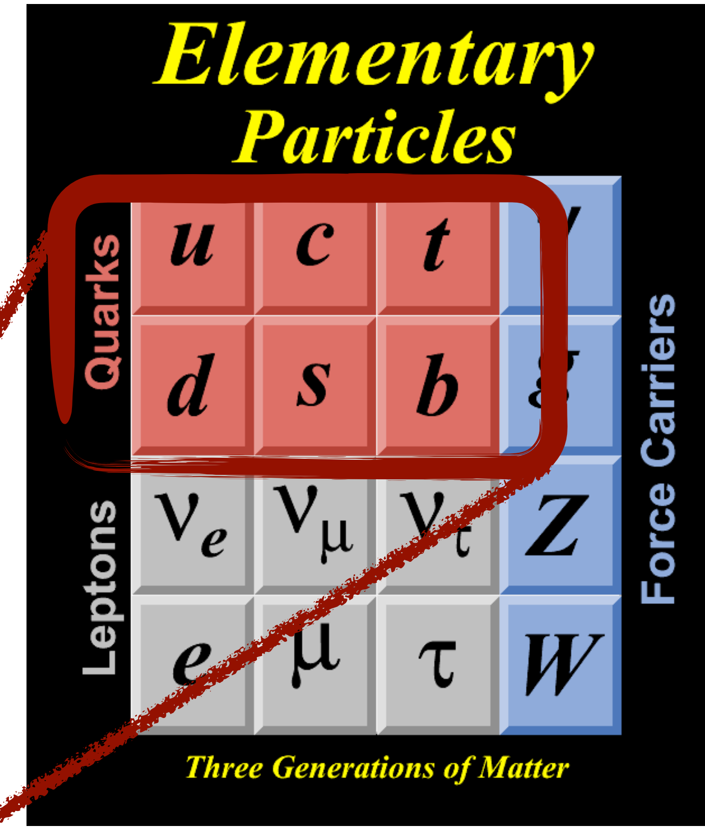
Henri Becquerel

Marie & Pierre Curie

- Scientists in the late 1800's and early 1900's made discoveries which would change the course of science, history and medicine.
- Henri Becquerel: Uranium salt "fogged" a photographic plate. This "Becquerel ray" ≠ x-ray. The discovery of radioactivity.
- Marie & Pierre Curie: Extracted uranium from ore; but the left-over had even more radioactivity → discovery of polonium and radium

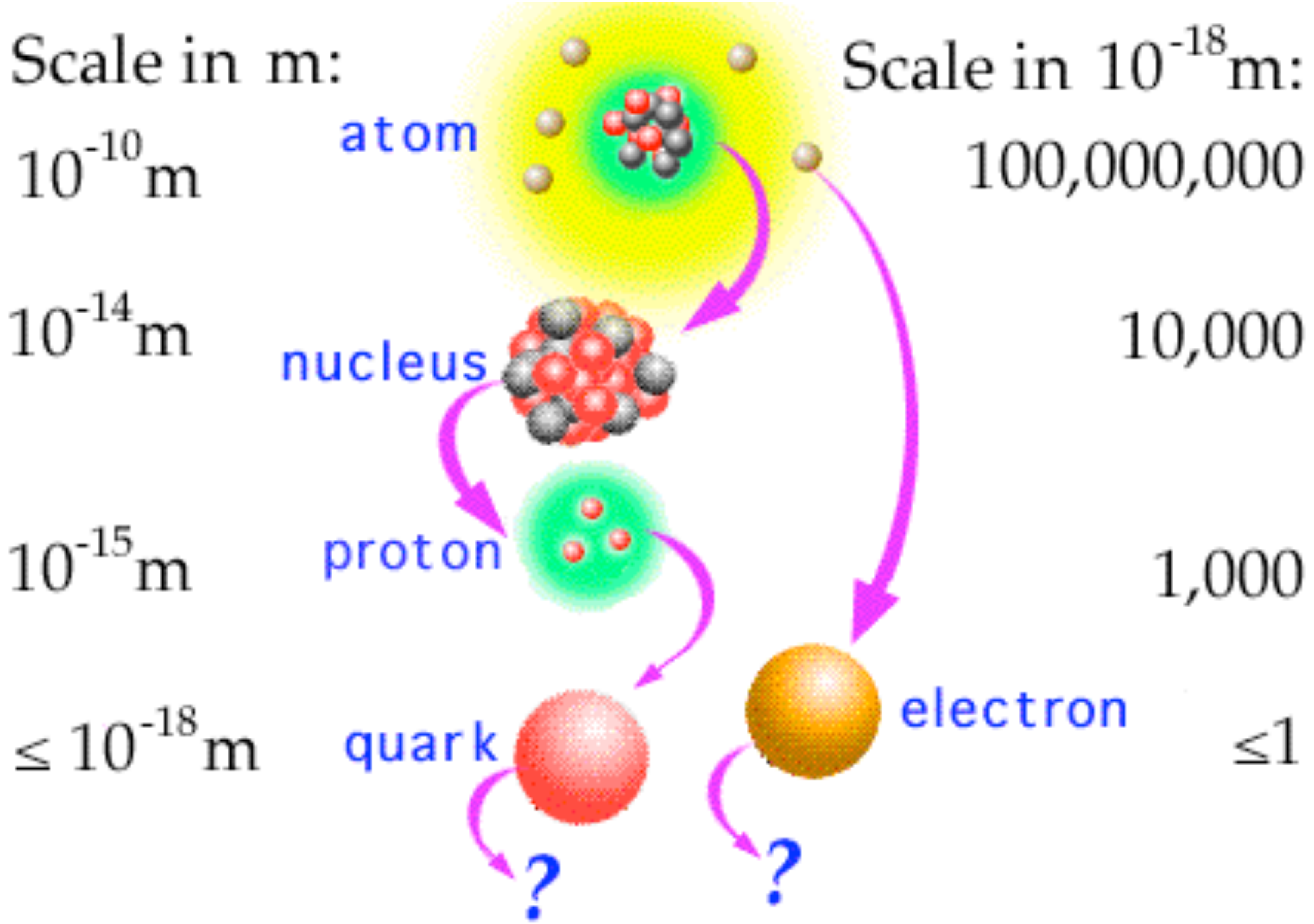
The nucleus





proton	u u d
neutron	u d d

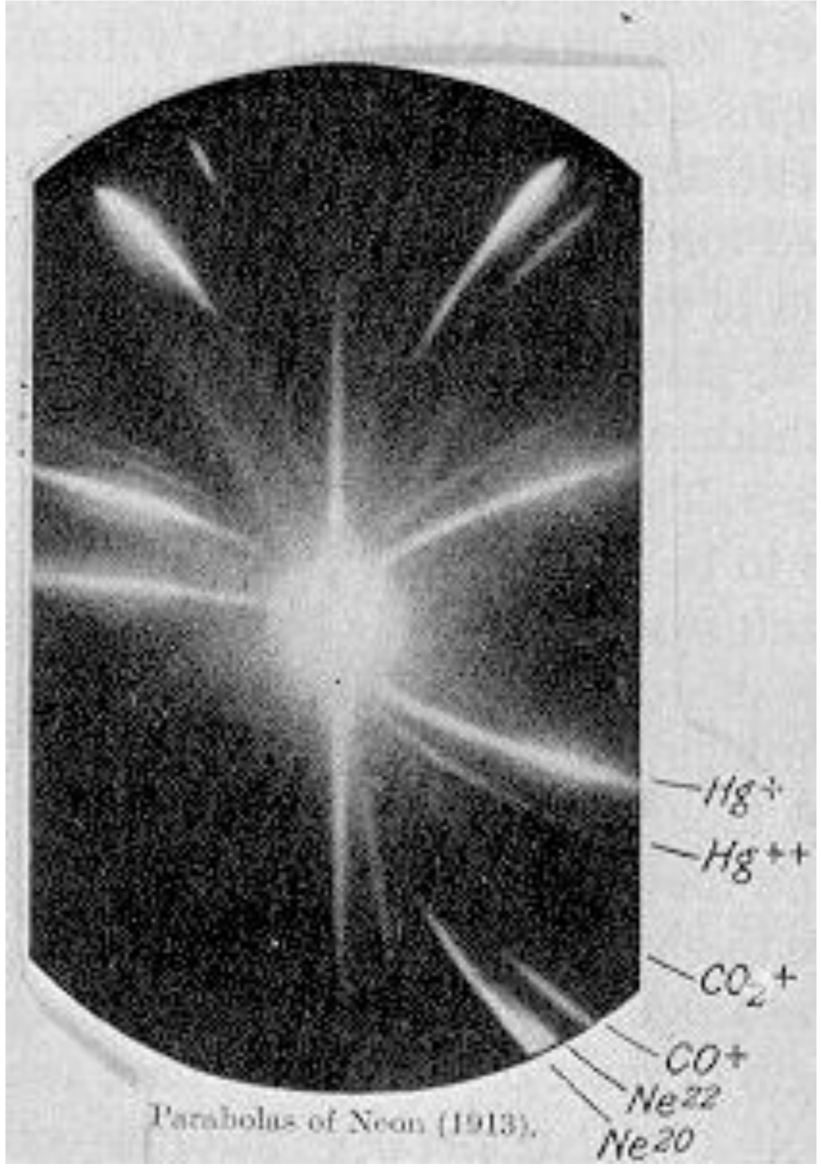
The nucleus



Scale in m:
Scale in 10^{-18}m:
10^{-10}m
atom
100,000,000
10^{-14}m
nucleus
10,000
10^{-15}m
proton
1,000
$\leq 10^{-18}$m
quark
electron
≤ 1
?
?

Isotopes

- J.J. Thomson sent Ne ions through electric and magnetic fields and saw two "beams" recorded on a photographic plate.
- F.W. Aston perfected the mass spectrograph to discover more isotopes.



$$^{A}_{Z}\textit{Symbol}_{N}$$

$$A = N + Z$$

A: mass number
N: # of neutrons
Z: atomic number

- Three isotopes of hydrogen:

Hydrogen	Deuterium	Tritium
$^{1}_{1}\mathrm{H}$	$^{2}_{1}\mathrm{H}$	$^{3}_{1}\mathrm{H}$

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Types of radioactivity

- **Radioactivity**: The spontaneous decay or disintegration of an unstable atomic nucleus accompanied by the emission of radiation.
- Three types:

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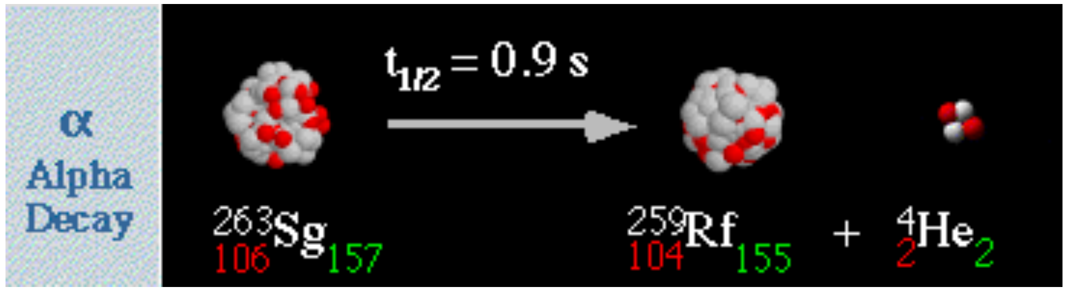

$$\alpha : (A, Z) \rightarrow (A-4, Z-2) + {}^{4}_{2}\mathrm{He}$$

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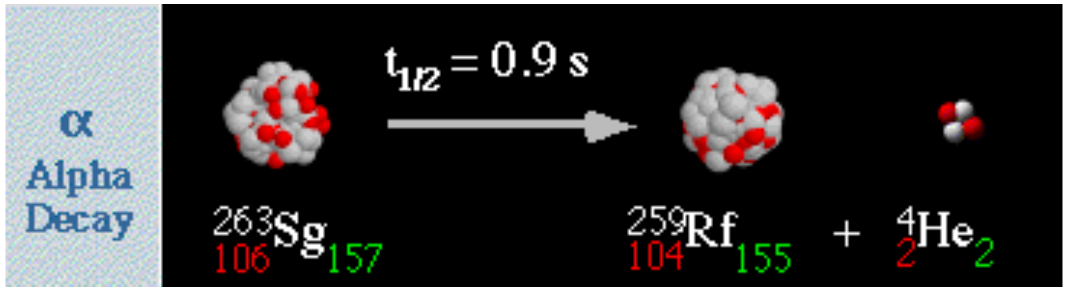

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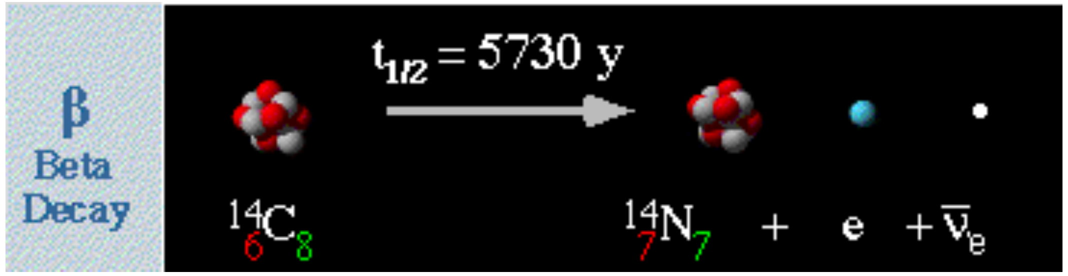

$$\beta^- : (A, Z) \rightarrow (A, Z+1) \ + \ e^- \ + \ \bar{\nu}_e$$

$$\beta^+ : (A, Z) \rightarrow (A, Z-1) \ + \ e^+ \ + \ \nu_e$$

Electron capture : $(A, Z) + e^- \rightarrow (A, Z-1) \ + \ \nu_e$

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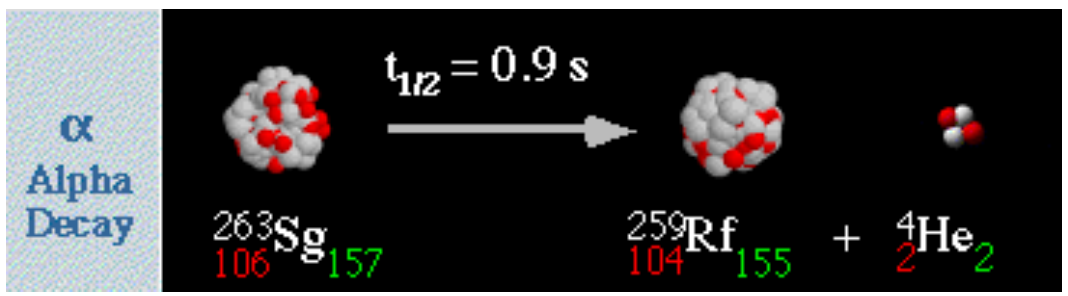
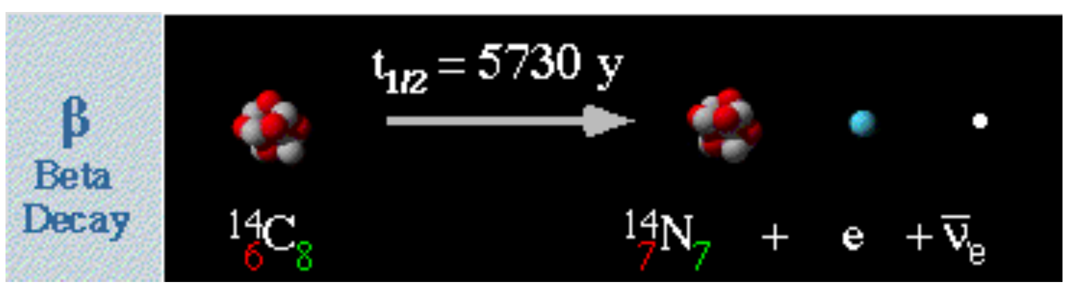


$$\alpha : (A, Z) \rightarrow (A-4, Z-2) \; + \; {}^4_2\mathrm{He}$$



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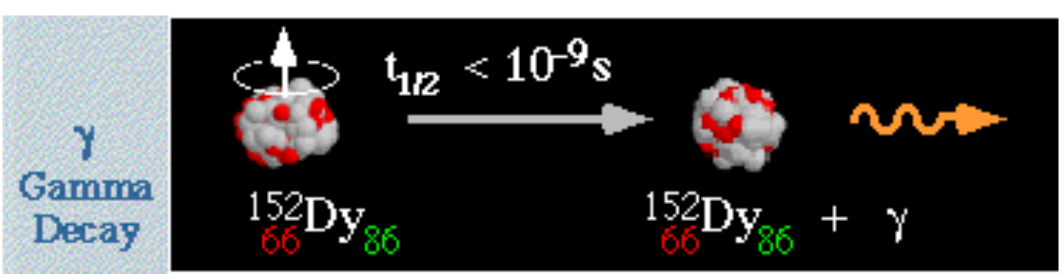
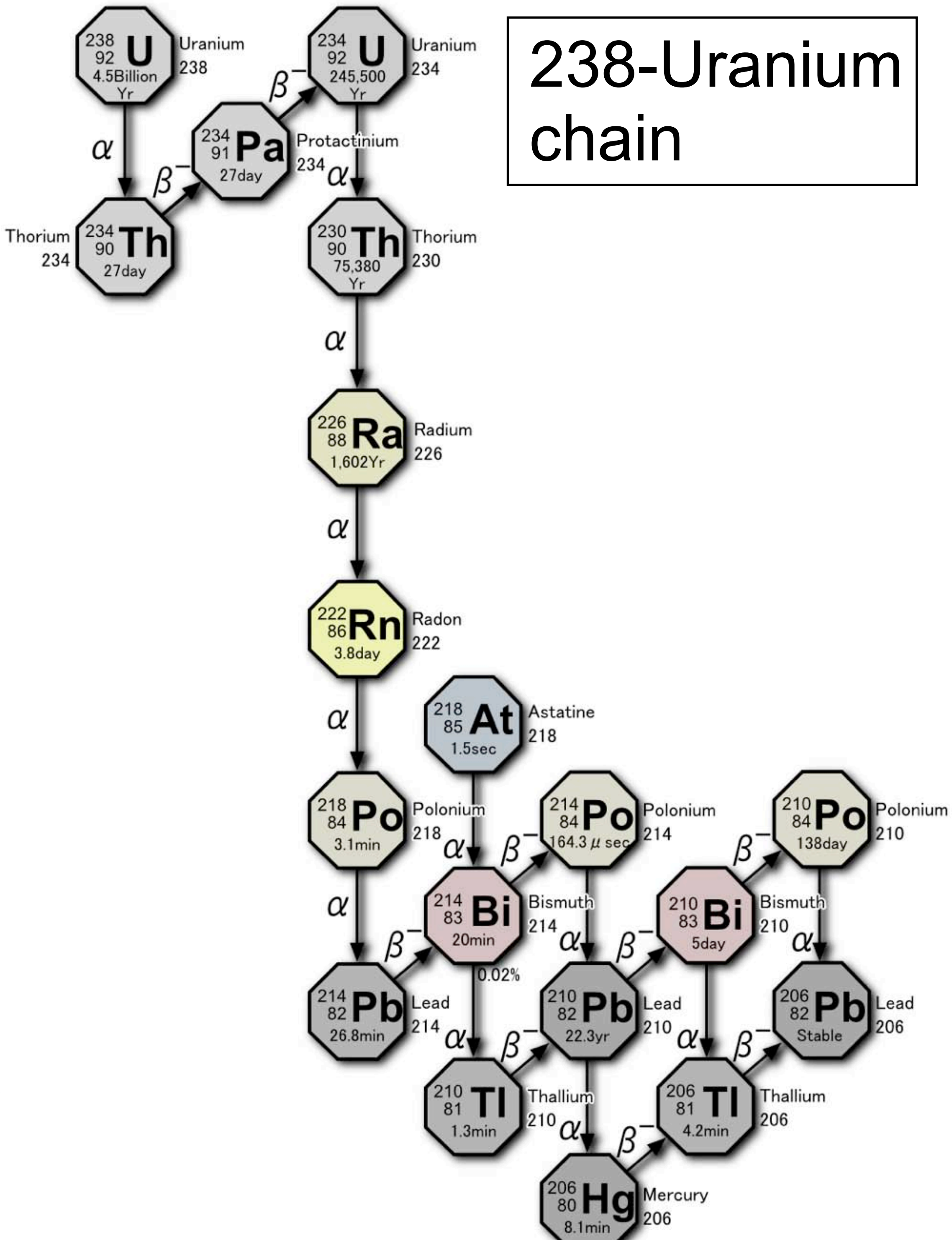


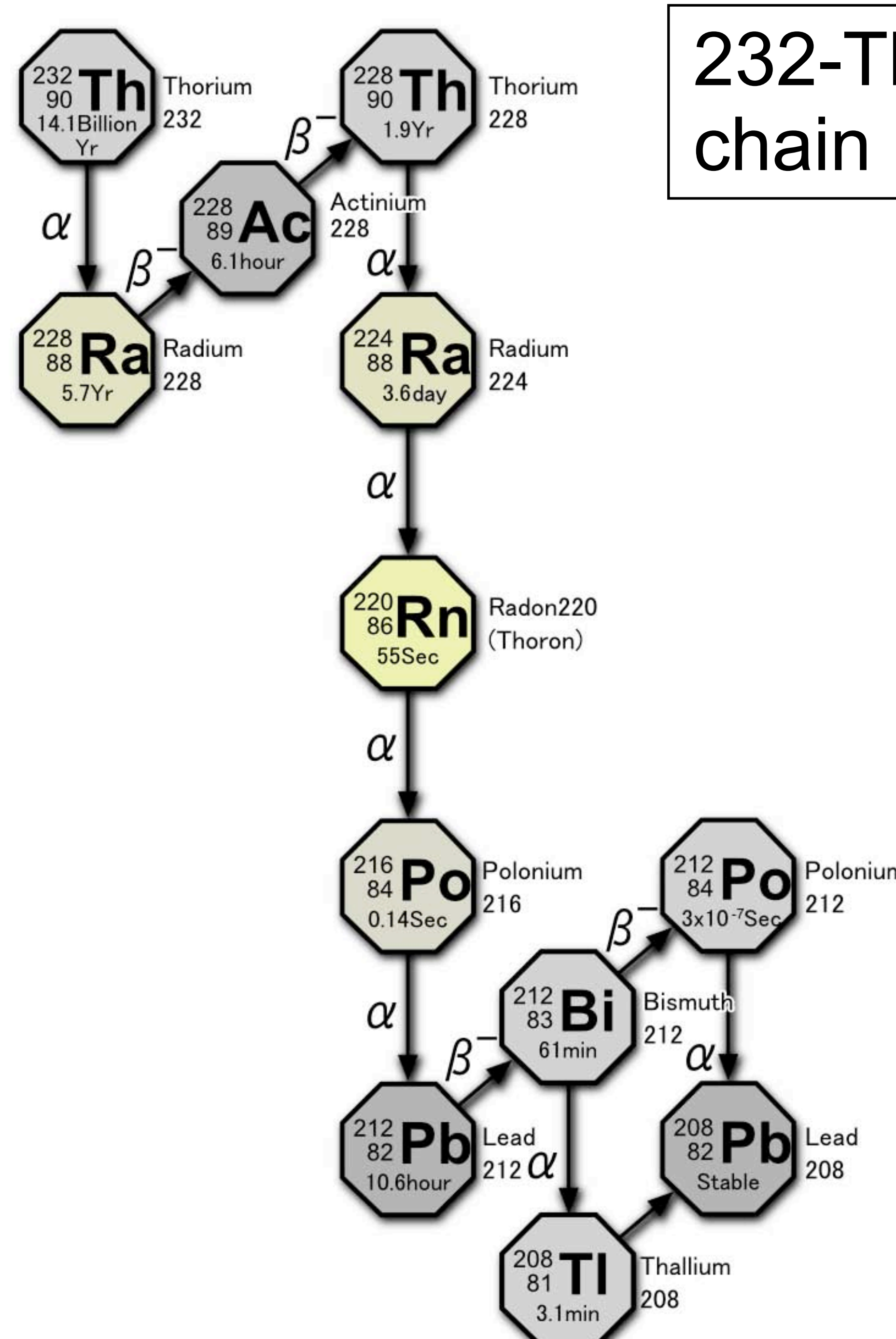
$$\gamma : (A, Z)^* \rightarrow (A, Z) \; + \; \gamma$$

Alpha decays

- Examples: natural decay chains



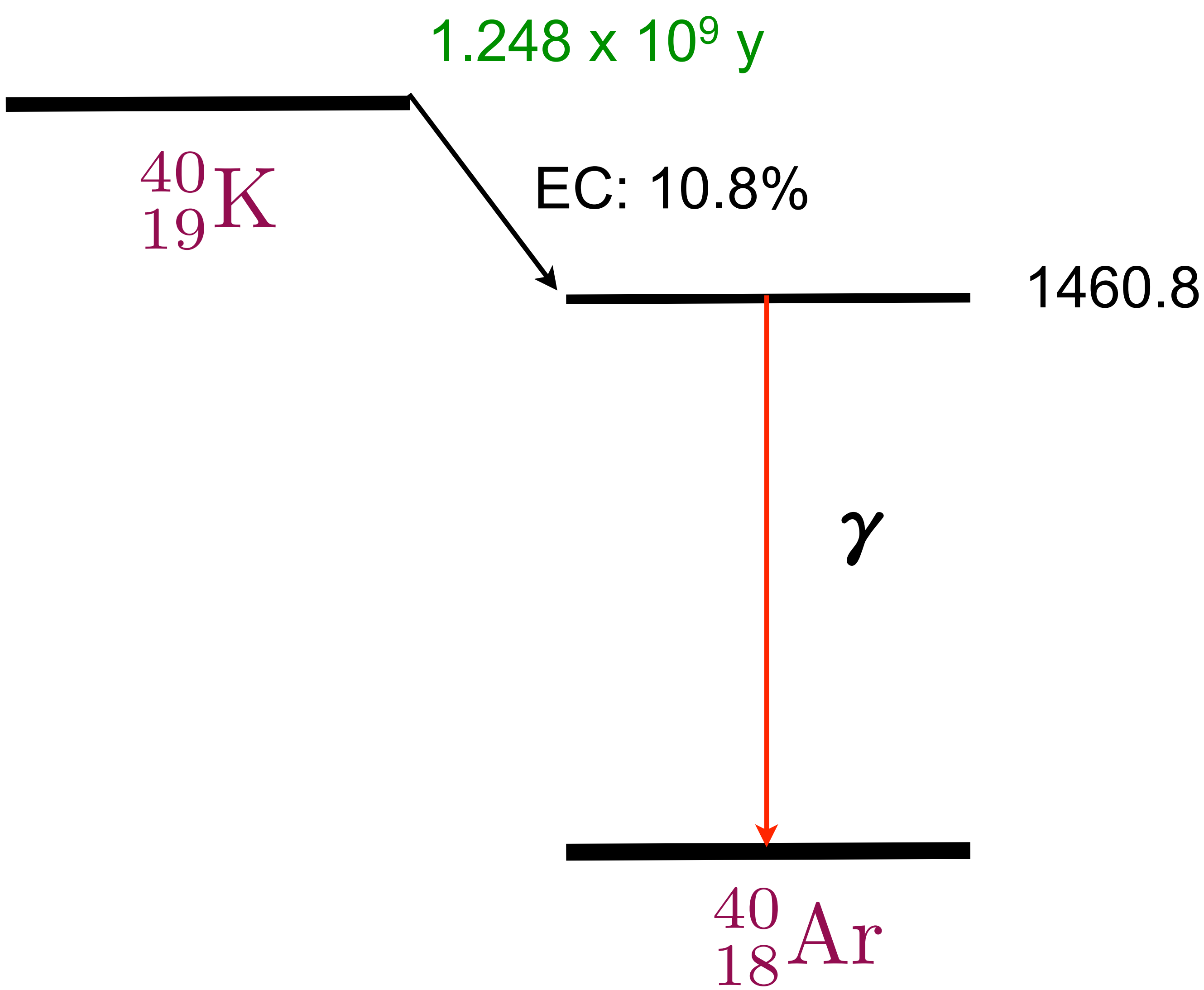
238-Uranium chain



232-Thorium chain

Beta and gamma decays

- Example: natural ^{40}K



Natural radioactivity: Do you know that...

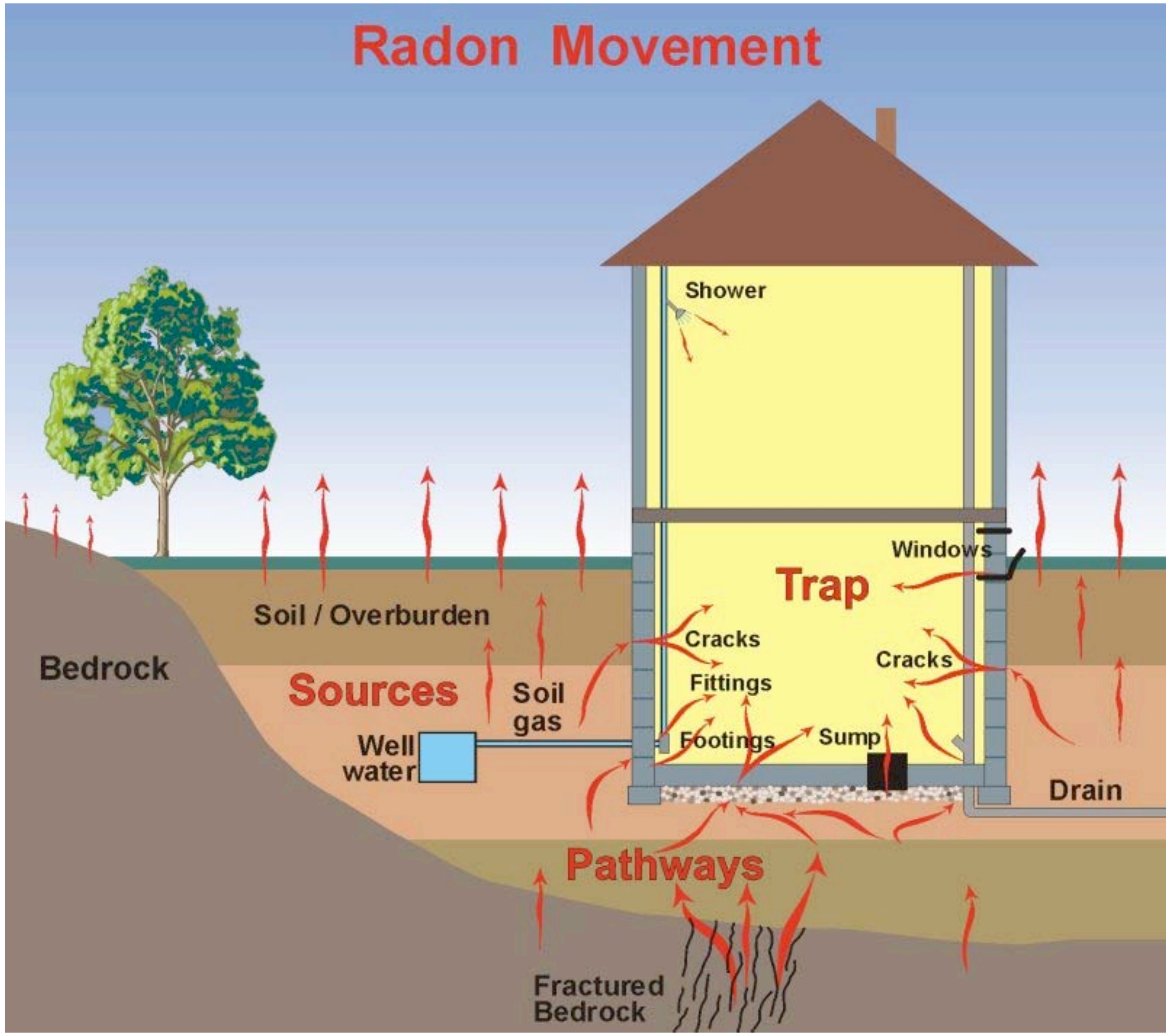
- Natural radioactive decays “power” our Earth

- *How do we know?*

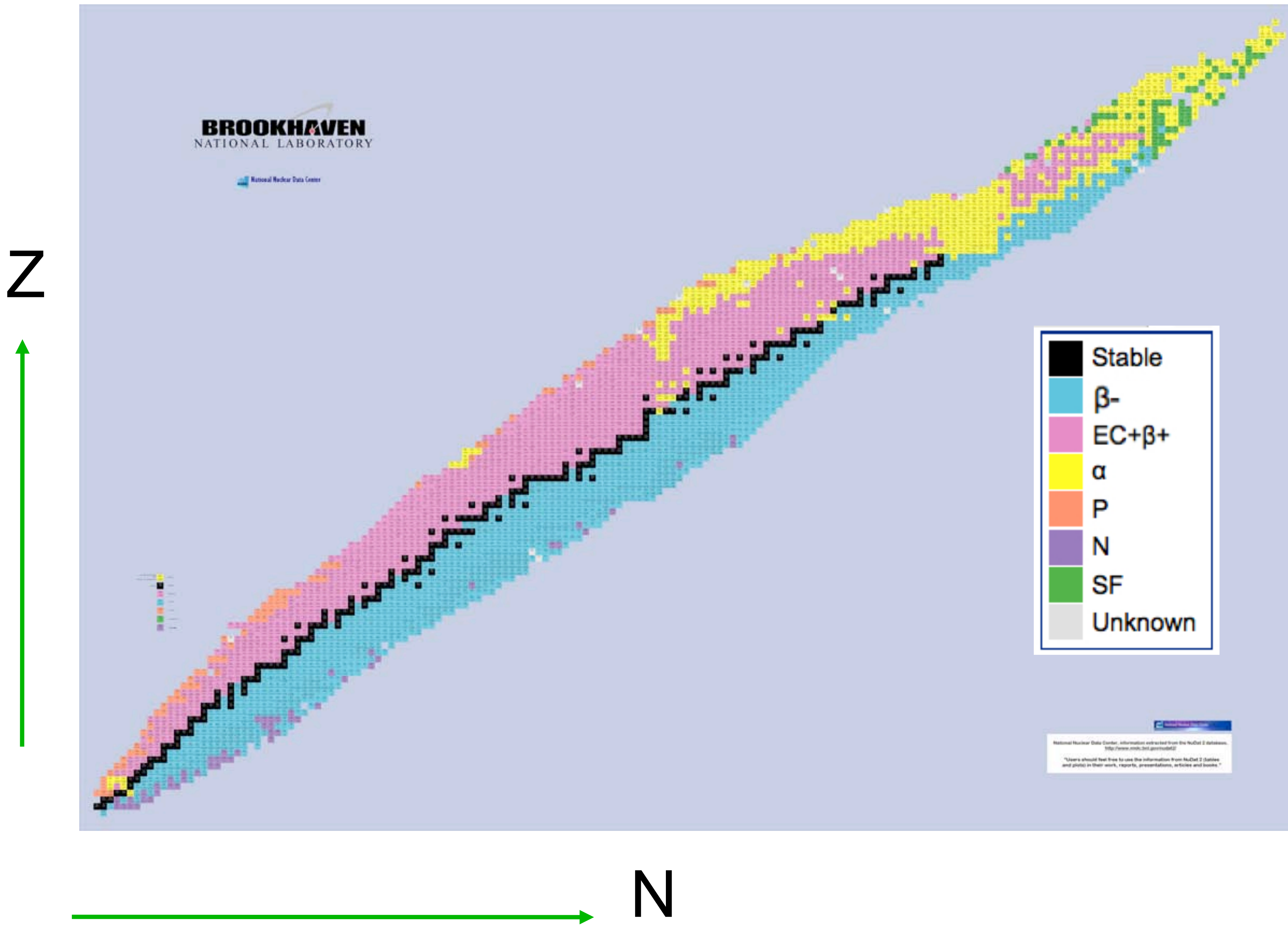
  We have observed the neutrinos from the beta decays (“geo-neutrinos”) in the chains.

Natural radioactivity: Do you know that...

- Radon is part of the decay chains



The Chart of the Nuclides: A “2-D” Periodic Table



- *Nuclei have shells similar to the electron shells in an atom. The electron shells determine the atomic and chemical properties; the nuclear shells determine the nuclear properties. Nuclei with filled shells (a “magic” number of neutrons or protons) are more stable.*
- *Moving from one box to neighboring boxes can be accomplished through nuclear reactions.*

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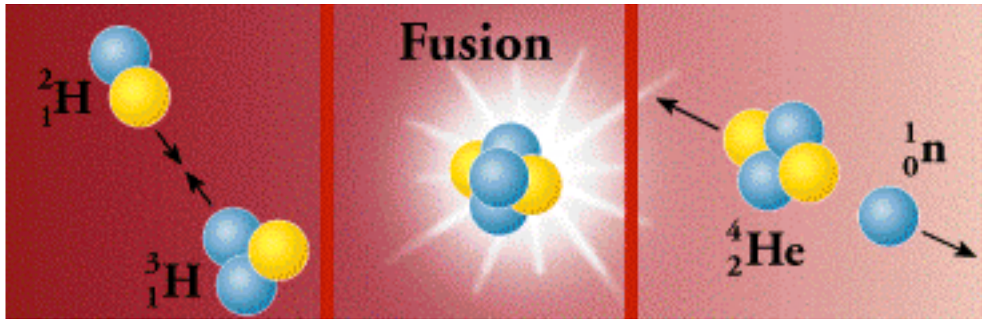
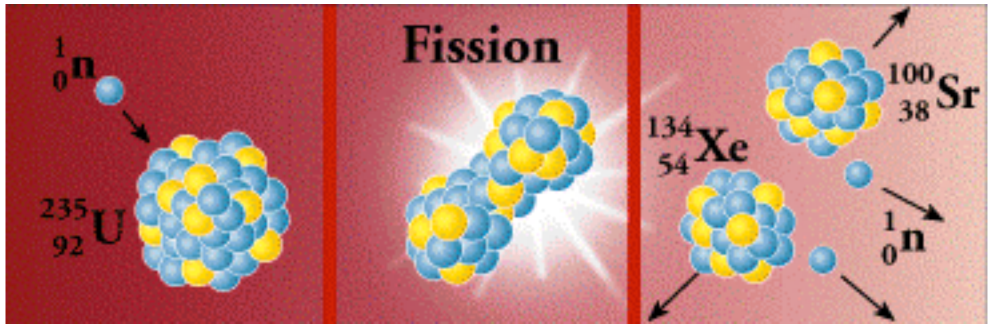
Nuclear reactions

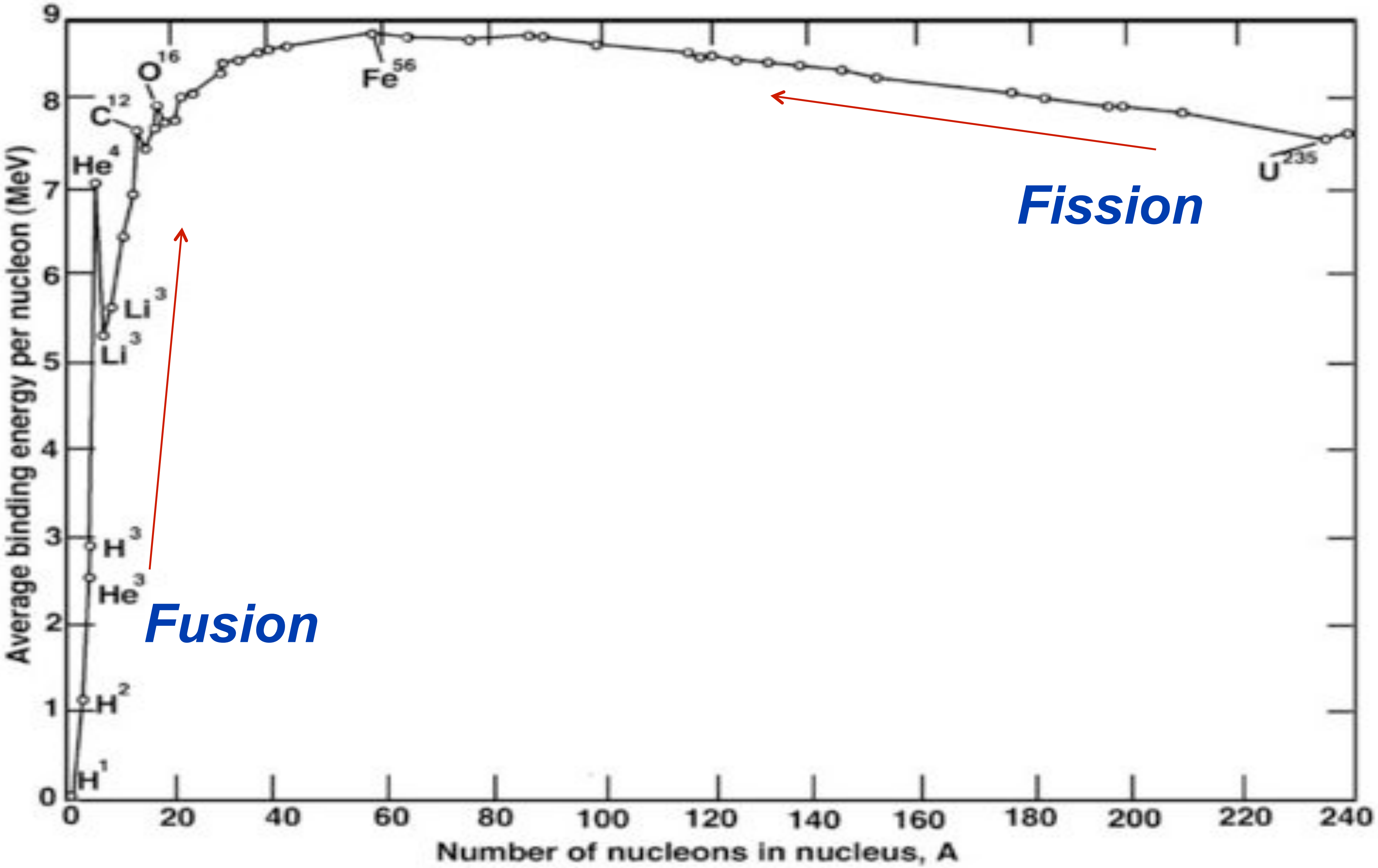
- Examples:
  - **Fusion**: how the Sun generates energy



  - **Fission**: how nuclear reactors generate energy



Nuclear binding curve



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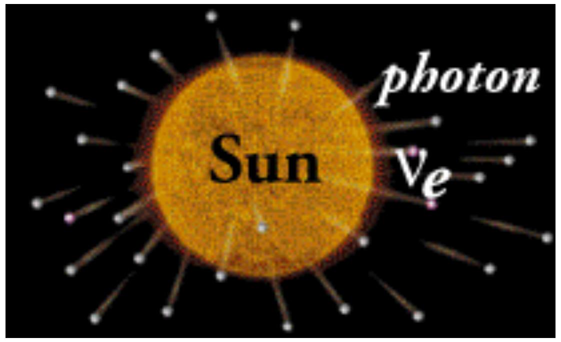
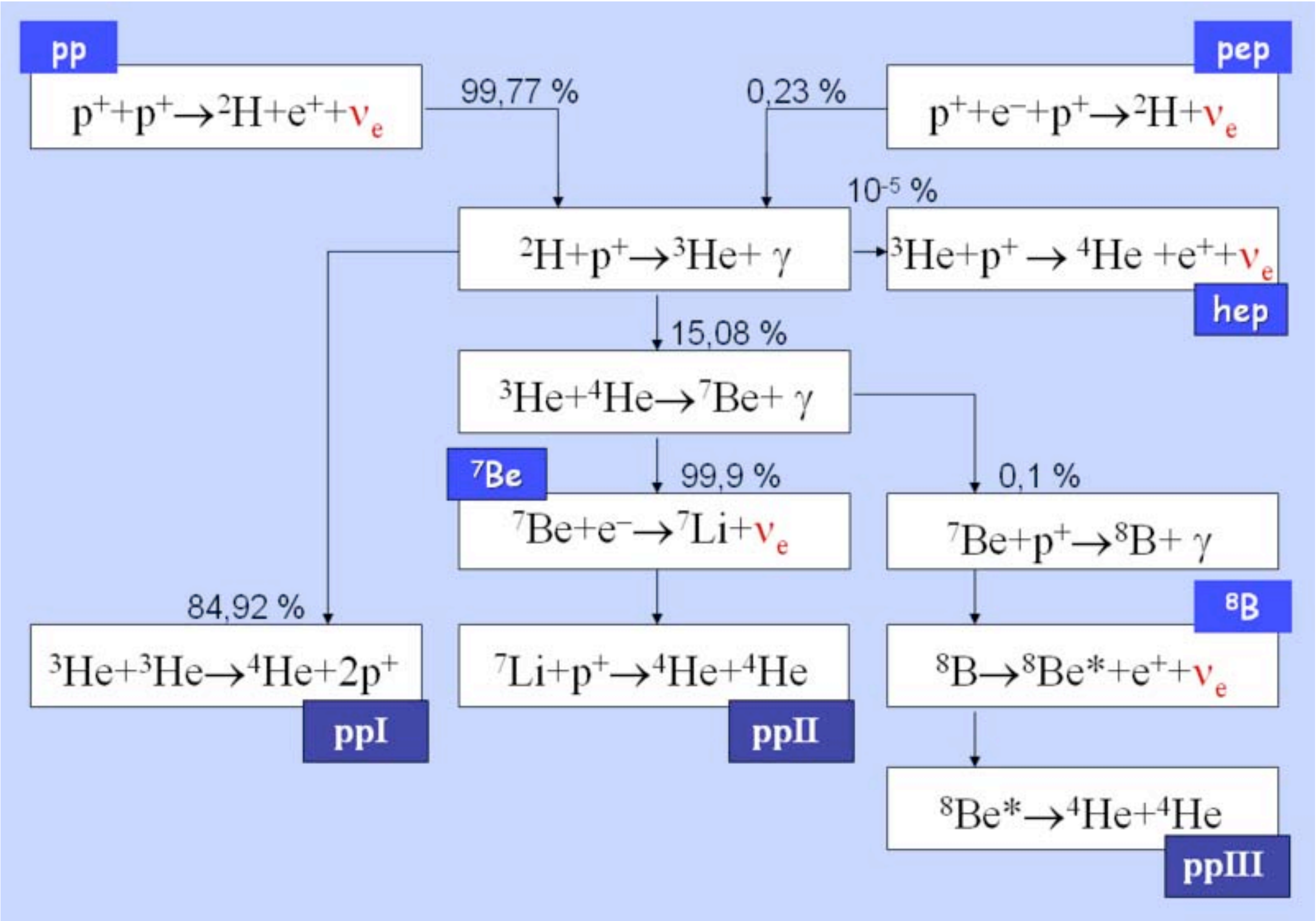
Nuclear reactions: Do you know that...?

- It takes thousands of years for light generated in the solar interior to reach the solar surface (and then another 8 minutes to reach us).

- The Sun generates energy in its core by fusing protons into ^{4}He through (mostly) the ***pp chain***.

- To prove that the Sun and other main sequence stars are powered by fusion, one can search for the neutrinos (which, unlike photons, don't get trapped in the solar interior)....right?





Nuclear reactions: detecting solar neutrinos

- First detection of solar neutrinos by Ray Davis, Jr. was a heroic effort.
- Ray Davis used this tank of cleaning fluid (615 t) C_2Cl_4 to detect solar neutrinos

$$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$$

- Flushed tank once a month, collected a few (if lucky) ^{37}Ar atoms in a glass vial (proportional counter) each time, look for its decay back to ^{37}Cl...for three decades!

"Ray Davis tells me that the experiment is simple (`only plumbing') and that the chemistry is `standard.' I suppose I must believe him, but as a nonchemist I am awed by the magnitude of his task and the accuracy with which he can accomplish it. The total number of atoms in the big tank is about 10^{30}. He is able to find and extract from the tank the few dozen atoms of ^{37}Ar that may be produced inside by the capture of solar neutrinos. This makes looking for a needle in a haystack seem easy." - J. Bahcall

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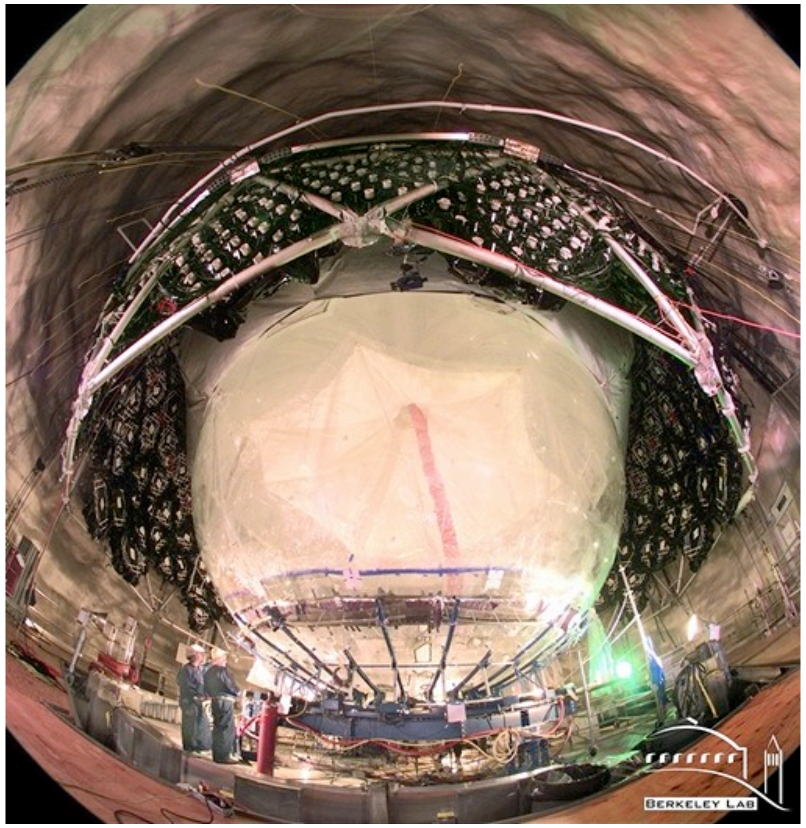
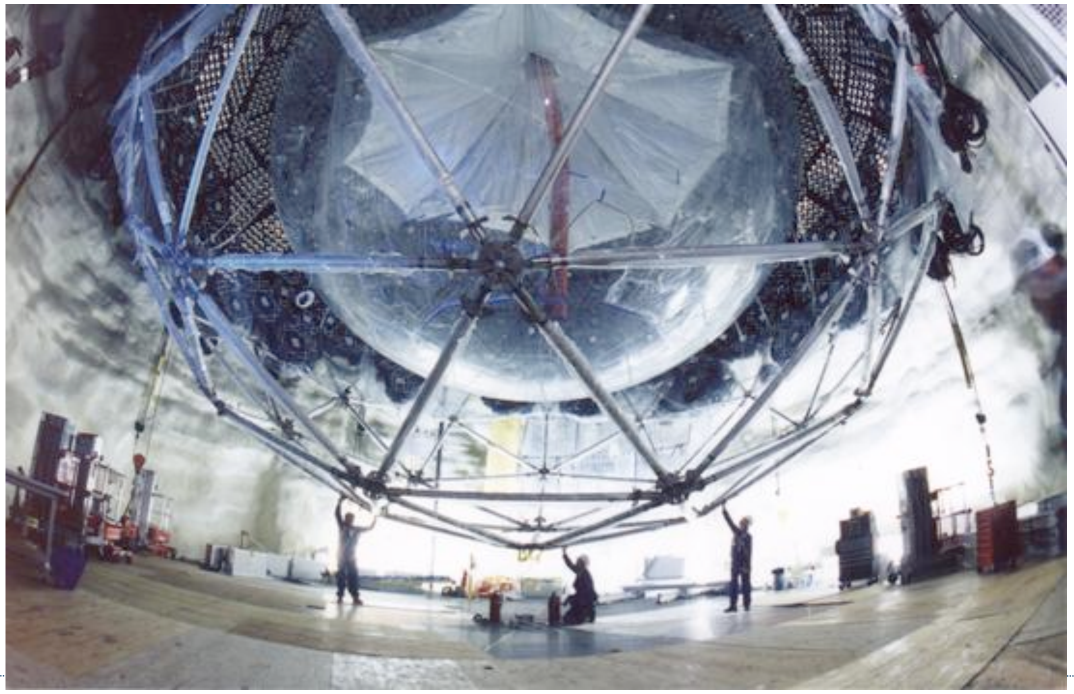
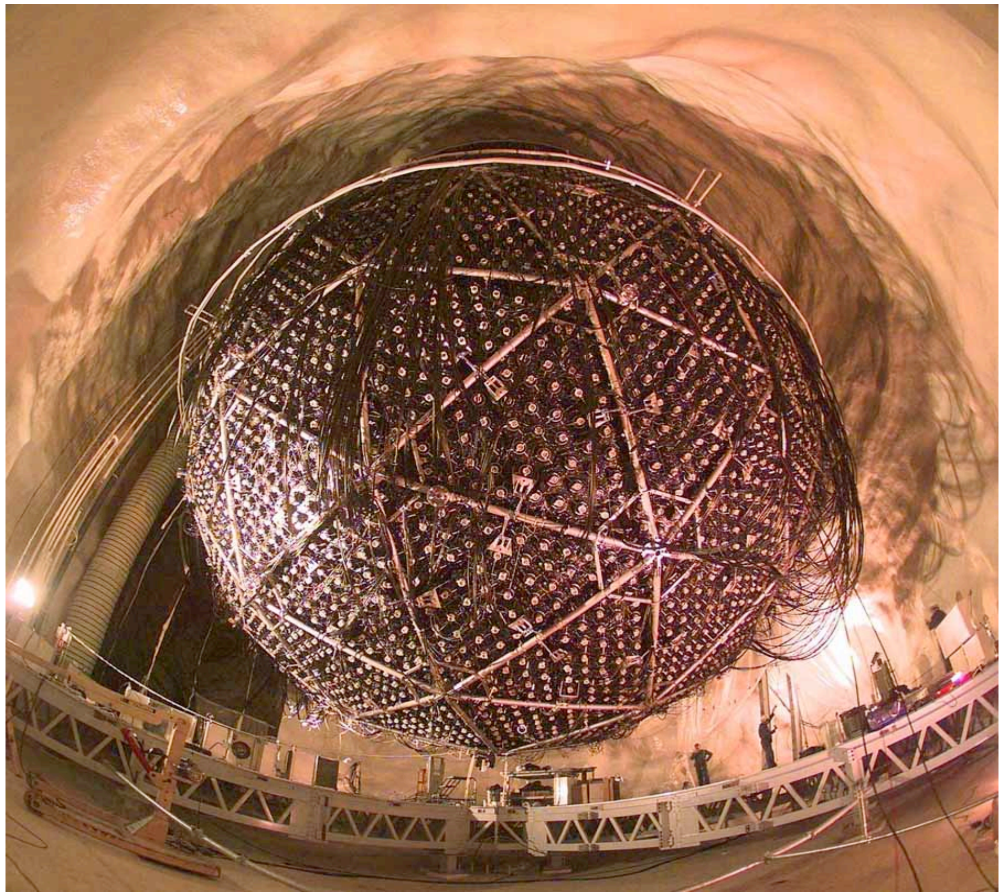
Aside: other neutrino experiments



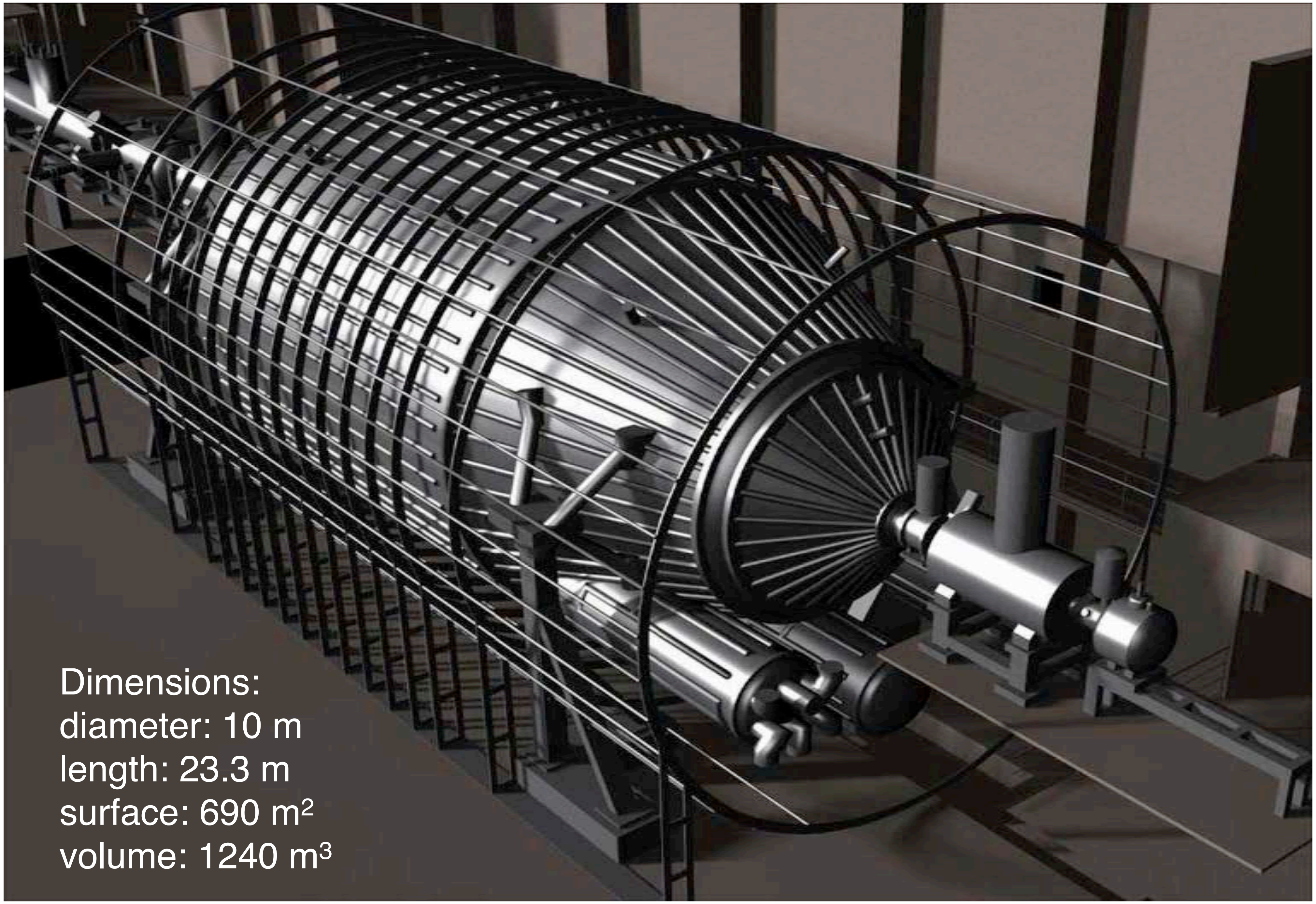


- **Sudbury Neutrino Observatory**: building a cleanroom in an active nickel mine 2 km underground



Aside: other neutrino experiments

- **KATRIN**: the largest ultra-high vacuum tank in the world



KATRIN

UNITED KINGDOM
IRELAND
Dublin
Belfast
London
Celtic Sea
Bay of Biscay
FRANCE
Paris
GERMANY
SPAIN
Madrid
PORTUGAL
Lisbon
ITALY
Rome
Mediterranean Sea
ALGERIA
MOROCCO
TUNISIA
POLAND
Warsaw
UKRAINE
BELARUS
ROMANIA
Bucharest
BULGARIA
Black Sea
TURKEY
GREECE
Athens
HUNGARY
Budapest
AUSTRIA
Vienna
Munich
Stuttgart
Rotterdam
Amsterdam
Scale 1: 19,500,000
Lambert Conformal Conic Projection, standard parallels 40°N and 56°N
300 Kilometers
300 Miles

KATRIN

UNITED KINGDOM
IRELAND
Dublin
Belfast
Irish Sea
Leeds
Manchester
Liverpool
Birmingham
Cardiff
London
Celtic Sea
Amsterdam
Rotterdam
NETH.
Hamburg
Bremen
Berlin
DENMARK
Copenhagen
Malmö
Bornholm
Gdańsk
Kaliningrad
RUSSIA
Vilnius
Minsk
Mahilyow
BELARUS
Hrodna
Homyel'
Poznań
Warsaw
POLAND
Łódź
Wrocław
Brest
Rivne
Kiev
UKRAINE
L'viv
Kraków
Essen
Cologne
Leipzig
Brussels
Lille
BEL.
Bonn
GERMANY
Frankfurt am Main
Prague
CZECH REPUBLIC
Brno
Luxembourg
LUX.
Guernsey (U.K.)
Jersey (U.K.)
Paris
Stuttgart
Strasbourg
Munich
Vienna
Bratislava
SLOVAKIA
Budapest
HUNGARY
AUSTRIA
Chernivtsi
Chişinău
Mykolayiv
Odesa
Iaşi
MOLDOVA
Cluj-Napoca
ROMANIA
Bucharest
Constanța
Black Sea
Nantes
FRANCE
Zürich
Bern
Vaduz
LIECH.
Geneva
Lyon
Bay of Biscay
Bordeaux
MASSIF CENTRAL
Milan
Turin
Venice
Ljubljana
SLOVENIA
Zagreb
CROATIA
BOSNIA AND HERZEGOVINA
Belgrade
Serbia
Sarajevo
Varna
BULGARIA
Sofia
Genoa
SAN MARINO
MONACO
Florence
Bilbao
Toulouse
Andorra la Vella
ANDORRA
PYRENEES
Marseille
Ligurian Sea
ITALY
Rome
VATICAN CITY
Adriatic Sea
Podgorica
Skopje
F.Y.R.O.M.
Tirana
ALB.
Thessaloniki
Istanbul
Bursa
TURKEY
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Scale 1: 19,500,000
Lambert Conformal Conic Projection, standard parallels 40°N and 56°N
300 Kilometers
300 Miles

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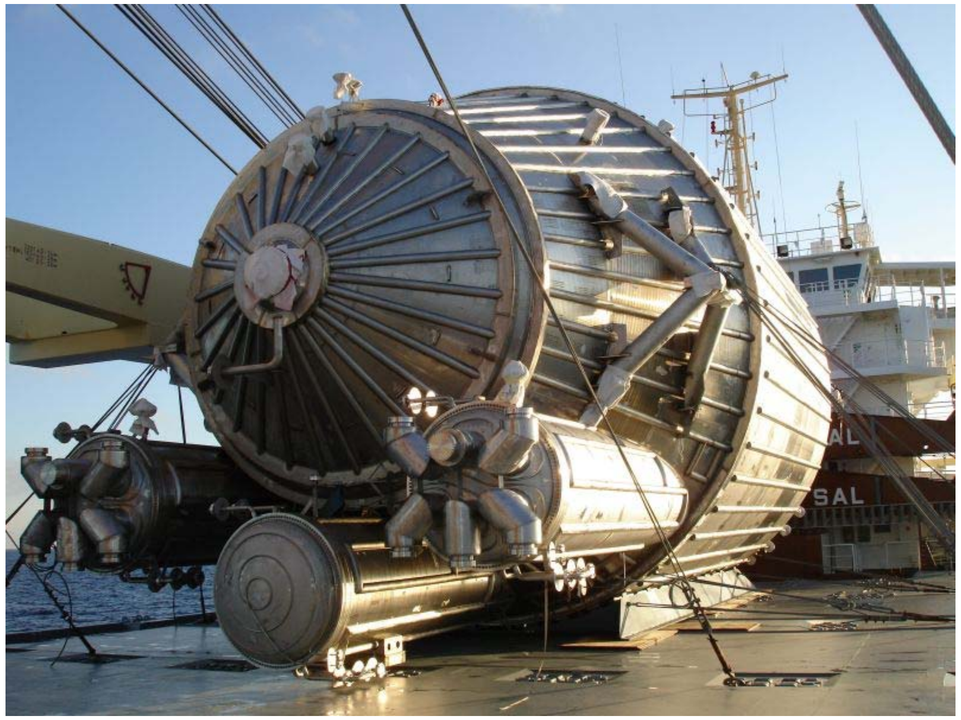

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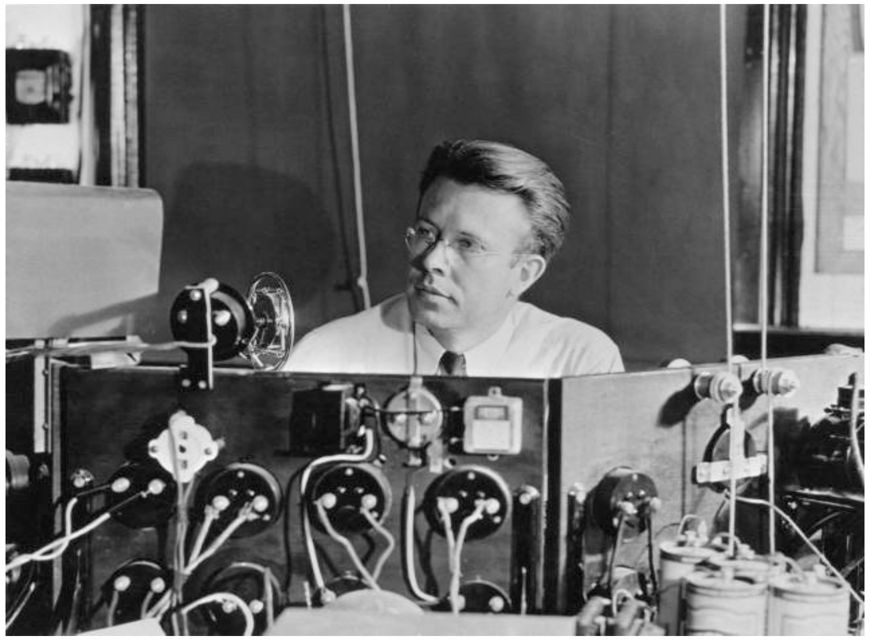
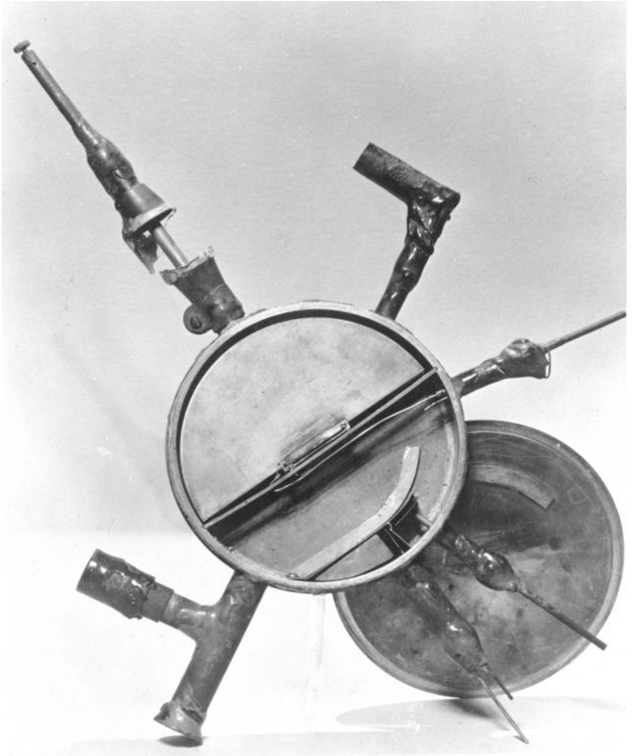
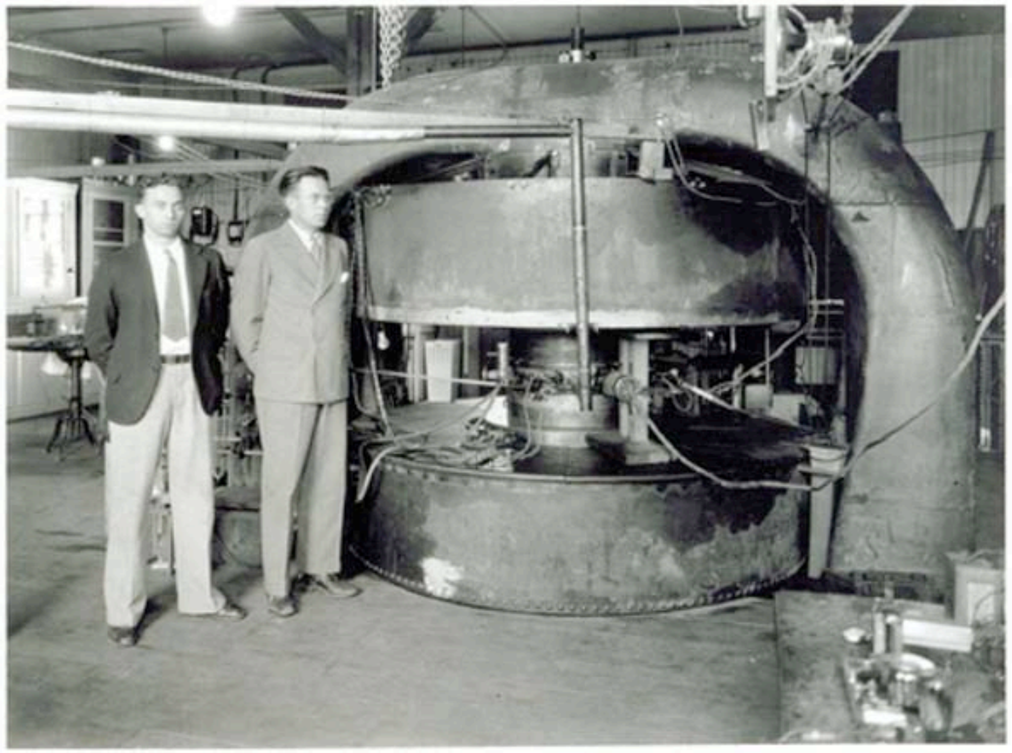
Accelerators: machines for nuclear studies (and a bit of local history)

- Ernest Orlando Lawrence invented the first cyclotron in 1929-31 in a small laboratory on the Berkeley campus. This was the foundation of the "Radiation Laboratory" (and later, Lawrence Berkeley National Lab, my current employer).





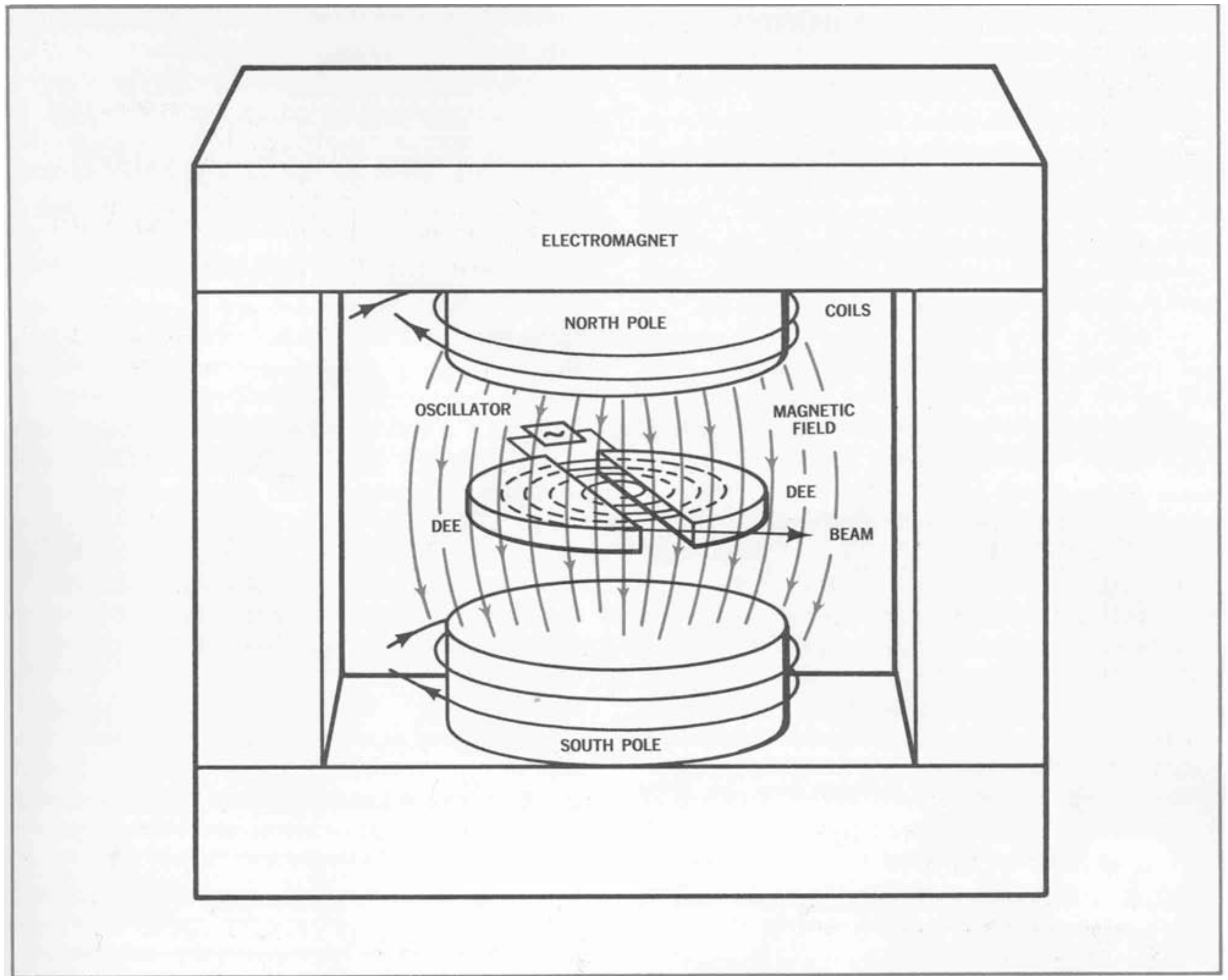
First cyclotron

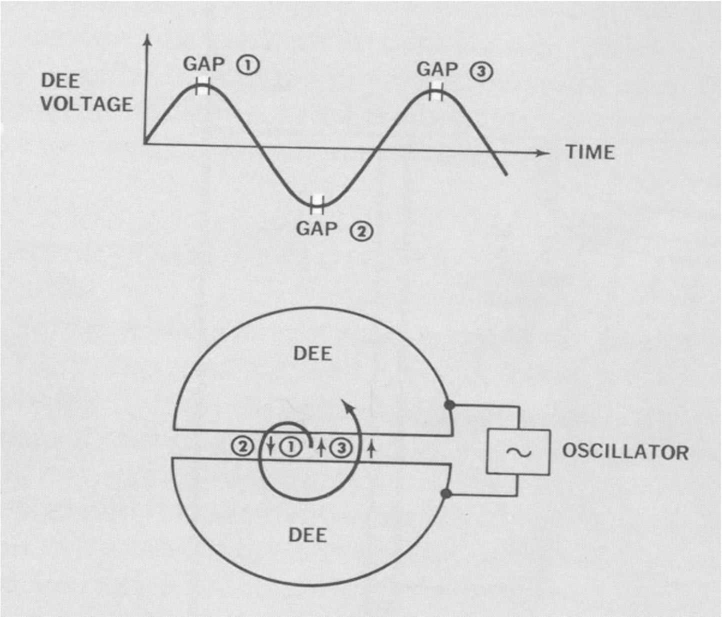


27" cyclotron; its magnet now outside LHS

- Cyclotrons are still used in physics research, and in cancer therapy and medical isotope production.

Accelerators: how does a cyclotron work?

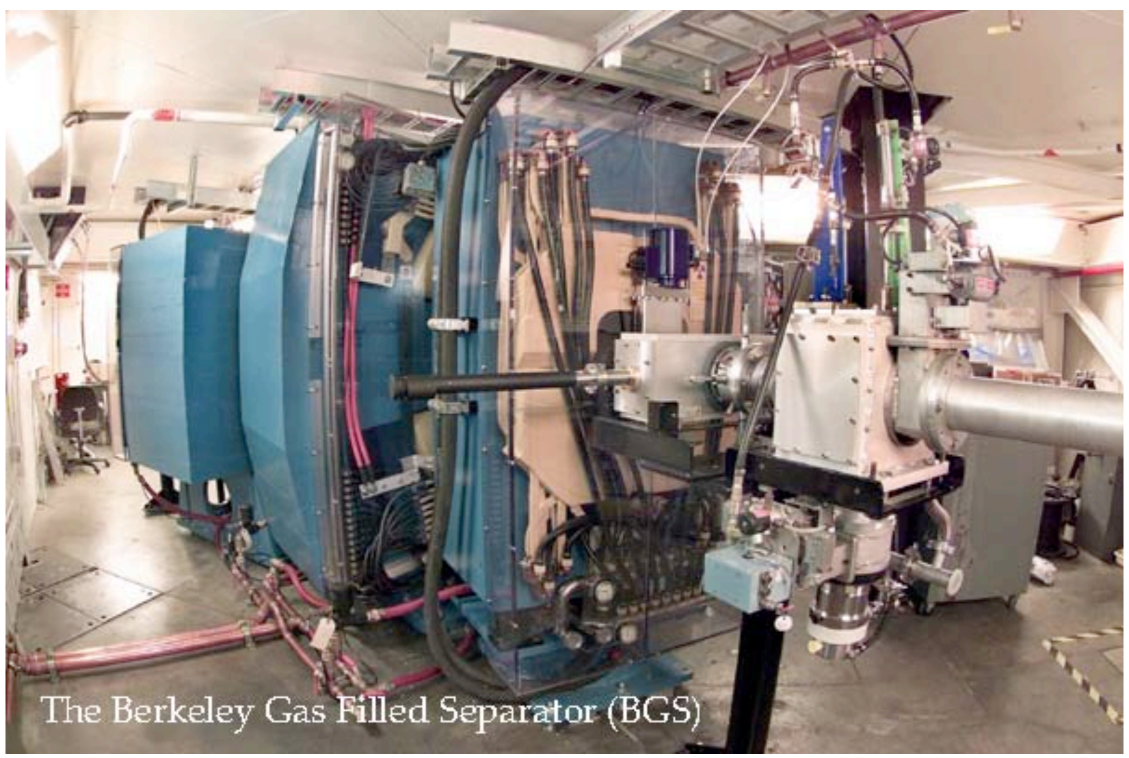


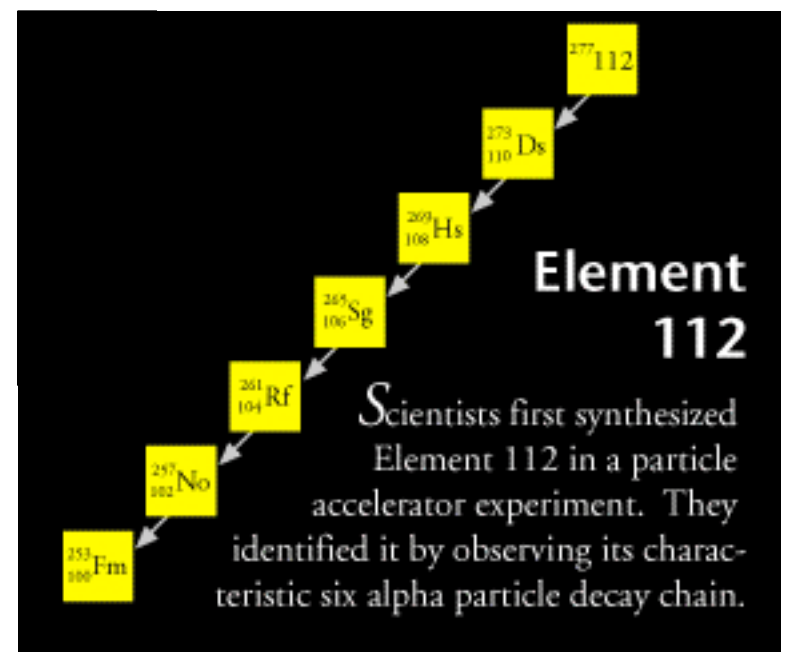


- It is left as an exercise for the students to show that the “cyclotron frequency” does not depend on the particles’ orbit radius if the particles are moving much slower than the speed of light.

Nuclear reactions: super heavy elements

- Super heavy elements can be “made” via nuclear reaction.
- For example for Z=112: $^{70}Zn + {}^{208}Pb \rightarrow {}^{278}112^{*}$
- To confirm their existence, first find and catch them, then look for tell-tale sequence of alpha decays.


The Berkeley Gas Filled Separator (BGS)



- Element 112 is recently named as Copernicium in honor of Nikolaus Copernicus.

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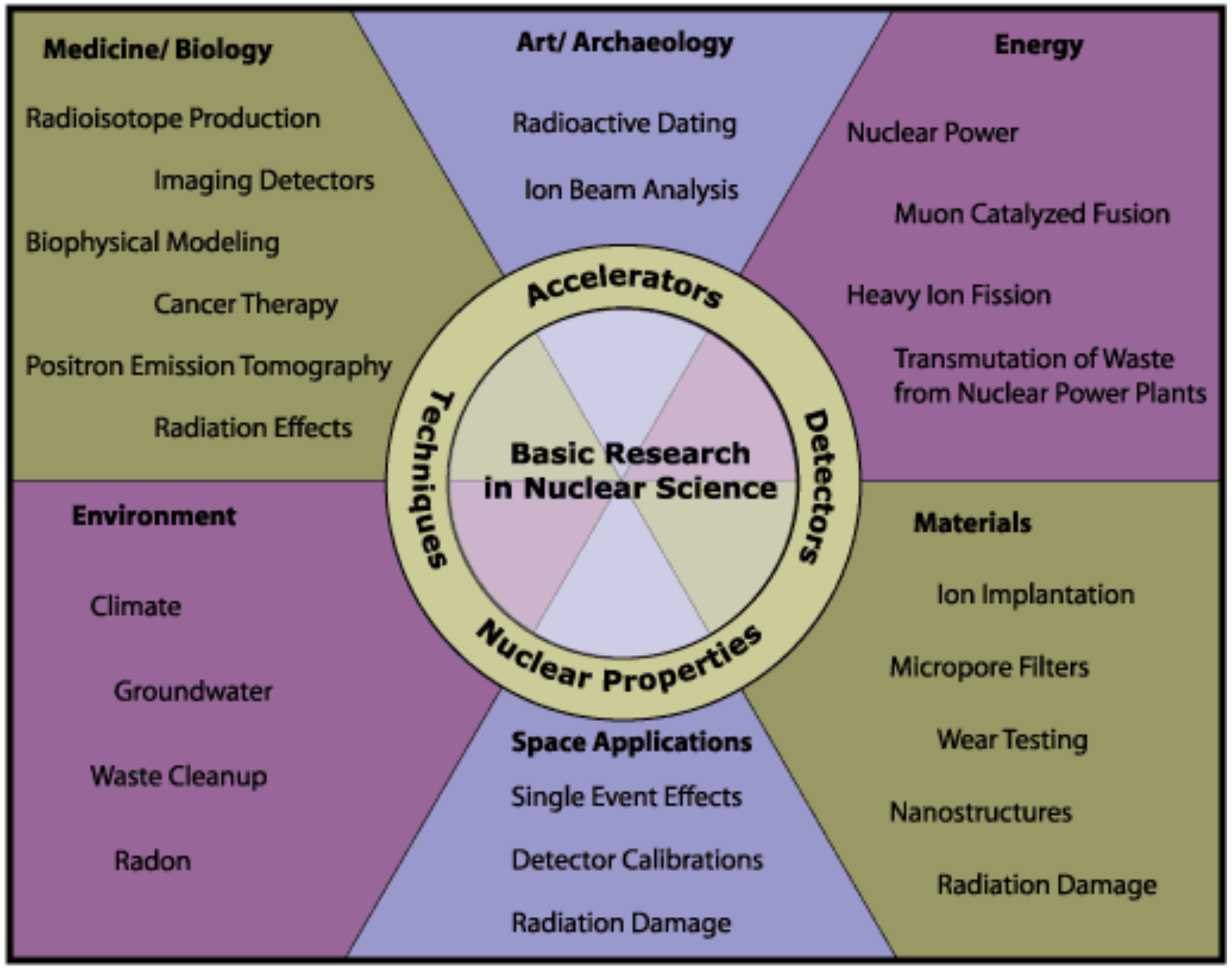
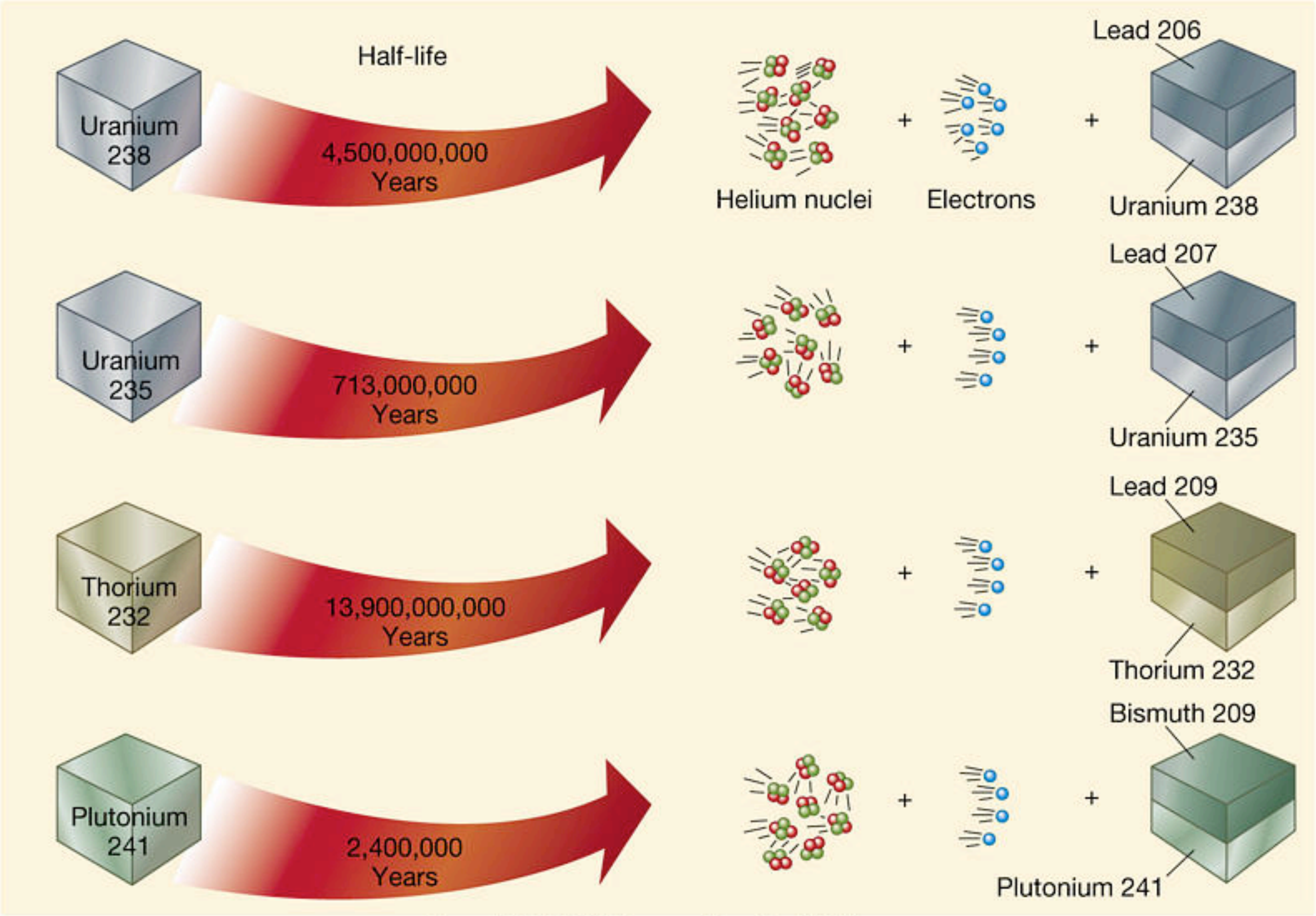
Applications of Nuclear Science

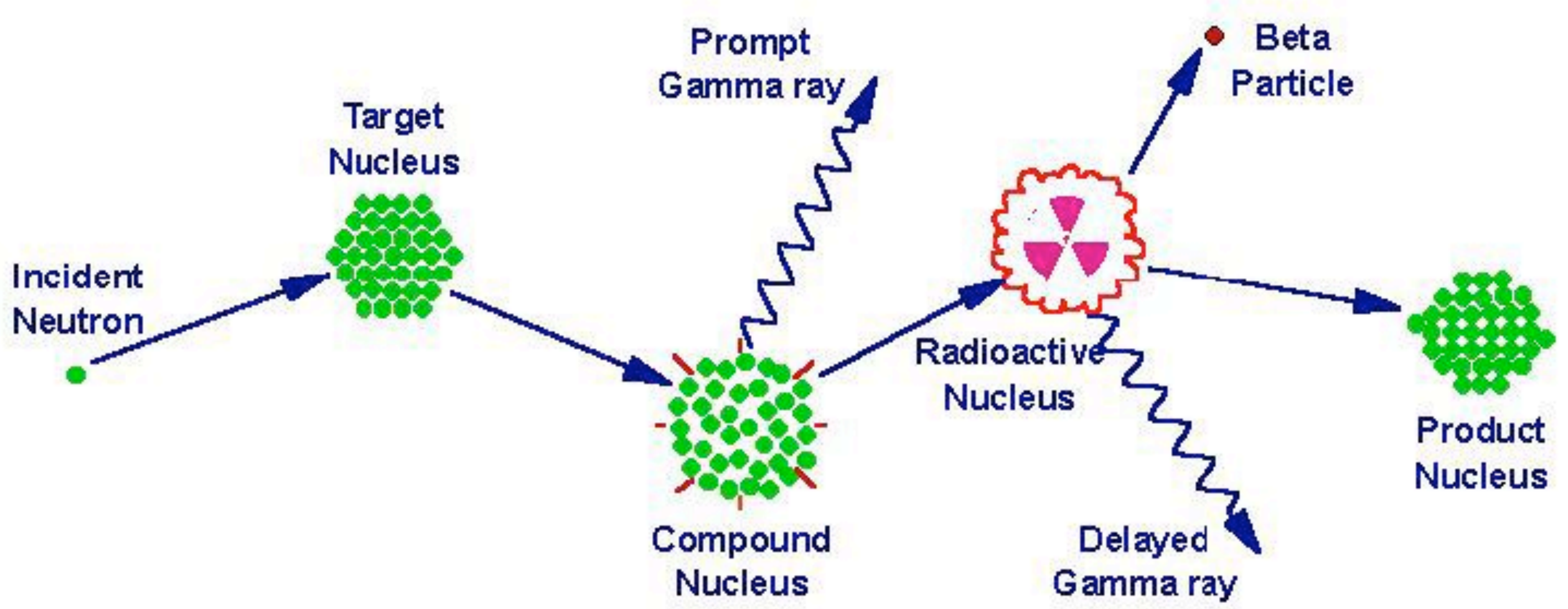


Radioactive dating



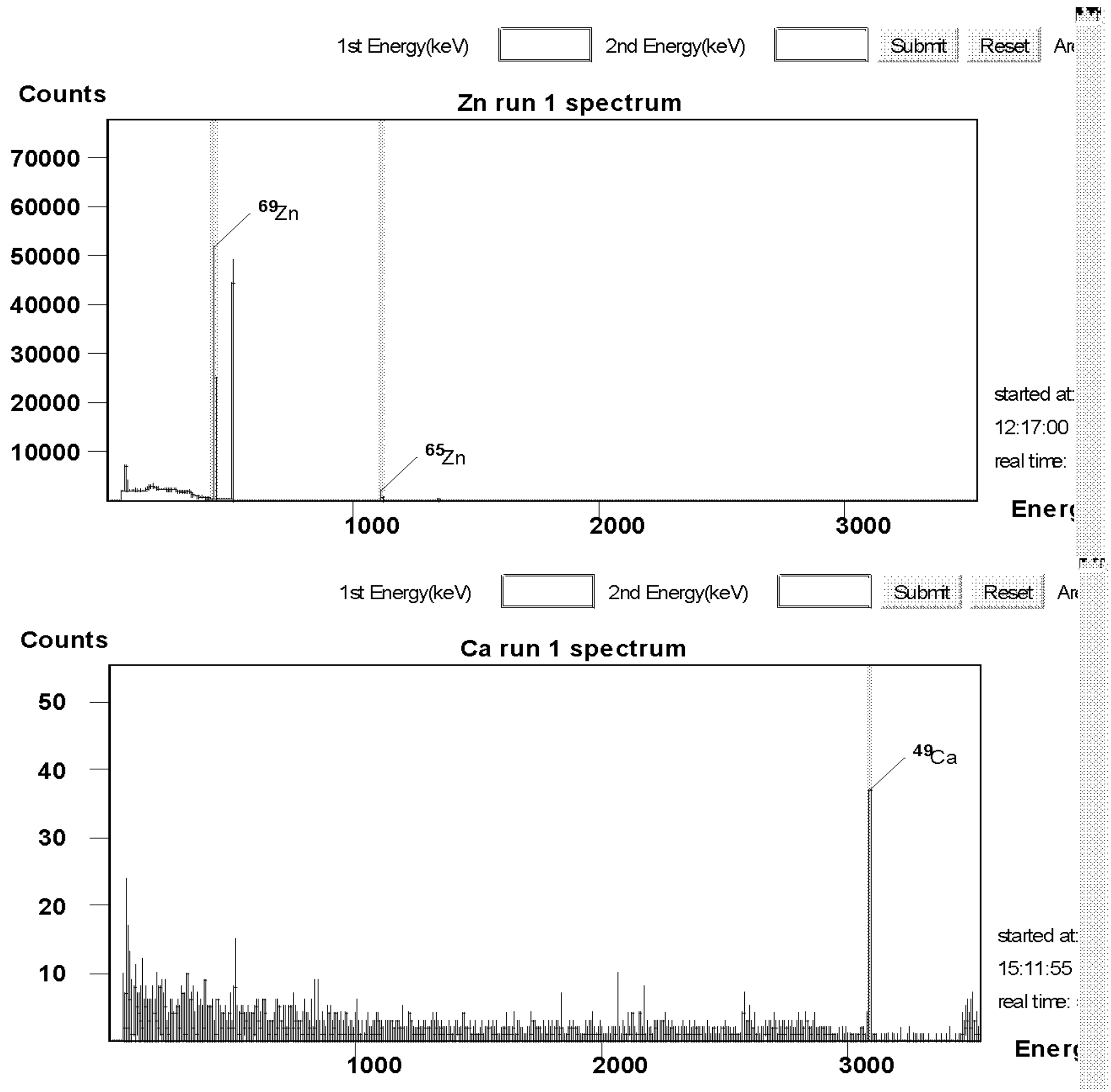
- Use highly sensitive mass spectrometers (modern version of Aston's) to determine parent and daughter nuclei concentrations

Neutron activation analysis



http://ie.lbl.gov/naa

Examples of NAA data



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Common use of radioactive isotopes

- **Self- luminous "EXIT" signs**. Tritium (^3H) gas is contained in sealed glass tubes, whose interior are lined with a phosphor. Low-energy β emitted by the tritium bombard the phosphor, causing it to glow.
- **Smoke detectors**. The current of alphas (^4He) from ^{241}Am decays entering an ionization chamber is reduced by the presence of smoke particulates, and the alarm is triggered.
- **Radiation sterilization** with ^{60}Co, UV light or X-rays. The radiation causes severe damage to the cell chromosomes, specifically the DNA, in bacteria.

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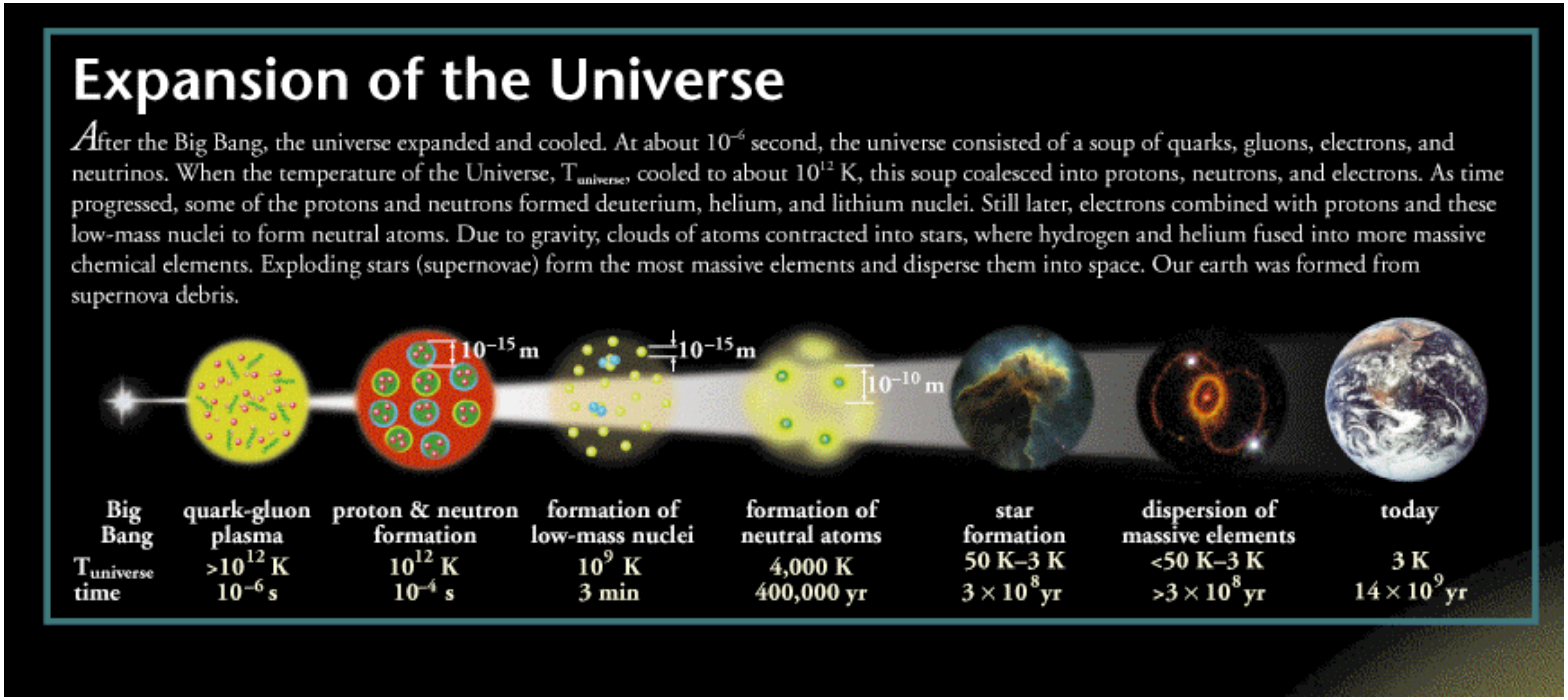
Our Universe



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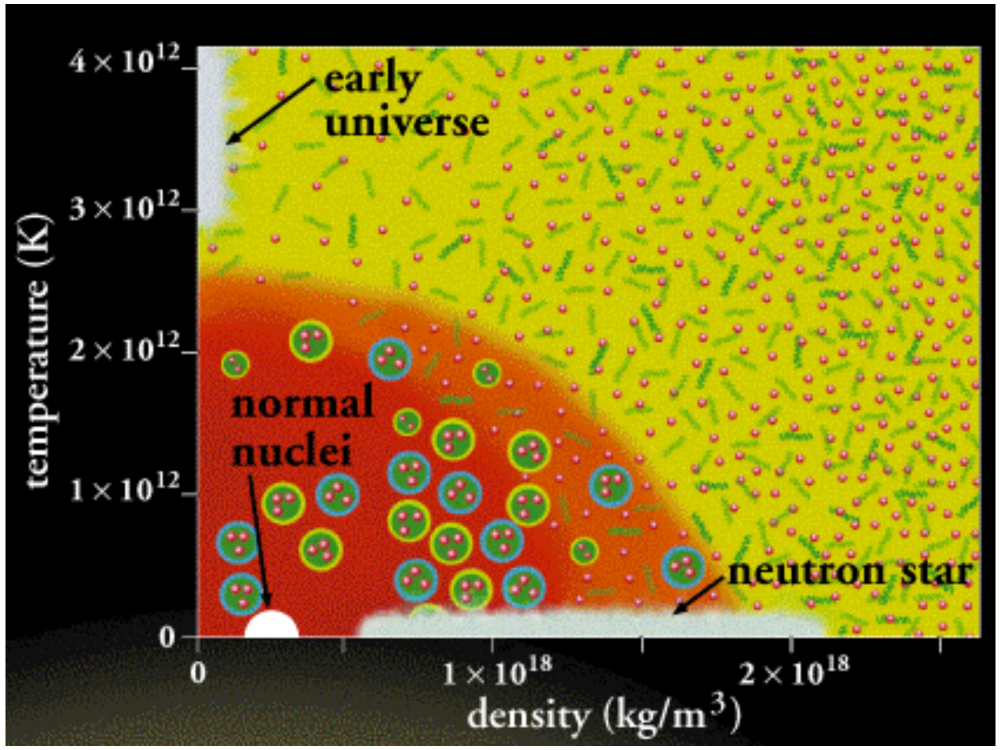
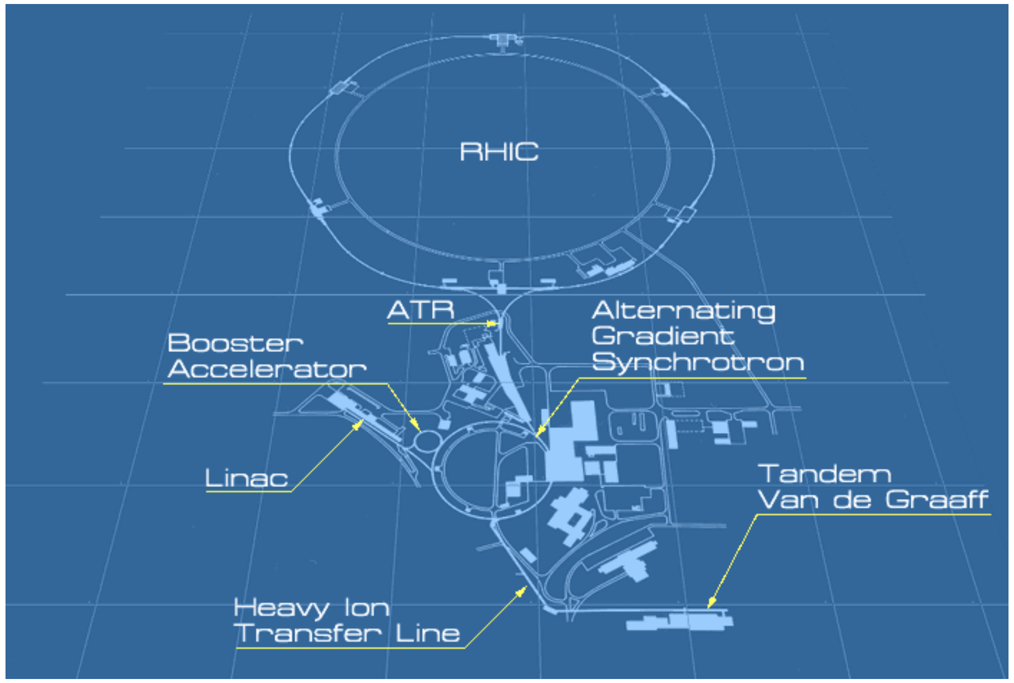
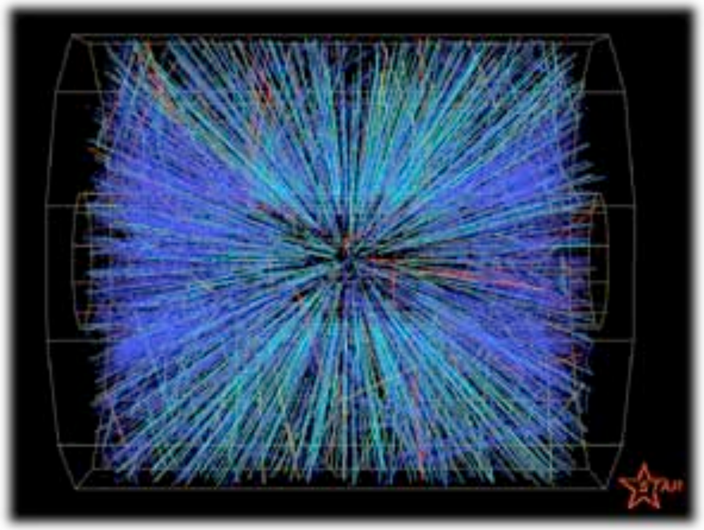
Quark-gluon plasma (QGP)

- **QGP**: A soup of (almost) free quarks and gluons that exists at extremely high temperature and/or density.





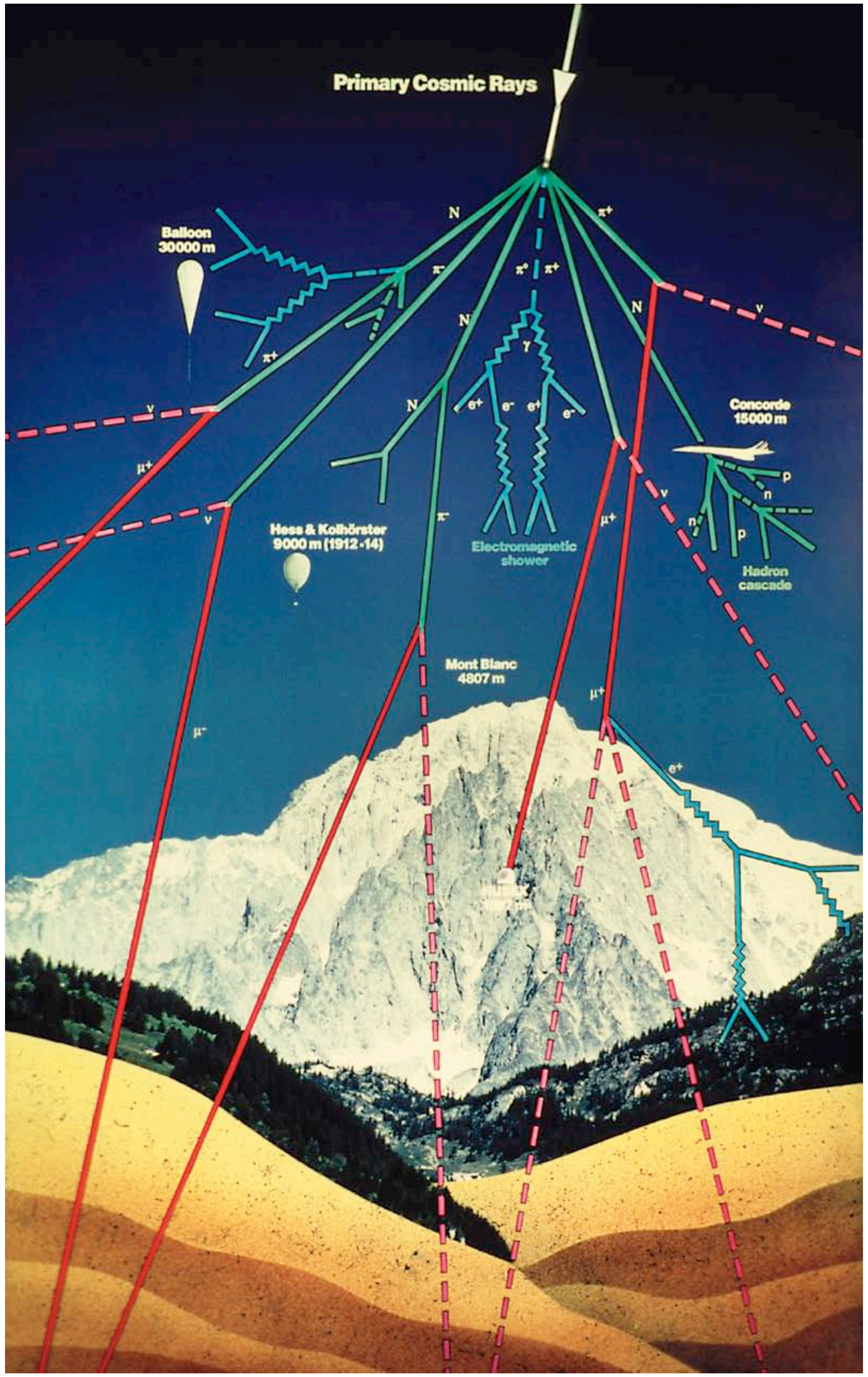
RHIC collider at Brookhaven National Lab



Au + Au collision in STAR detector at RHIC

More details in: http://www.youtube.com/watch?v=kXy5EvYu3fw

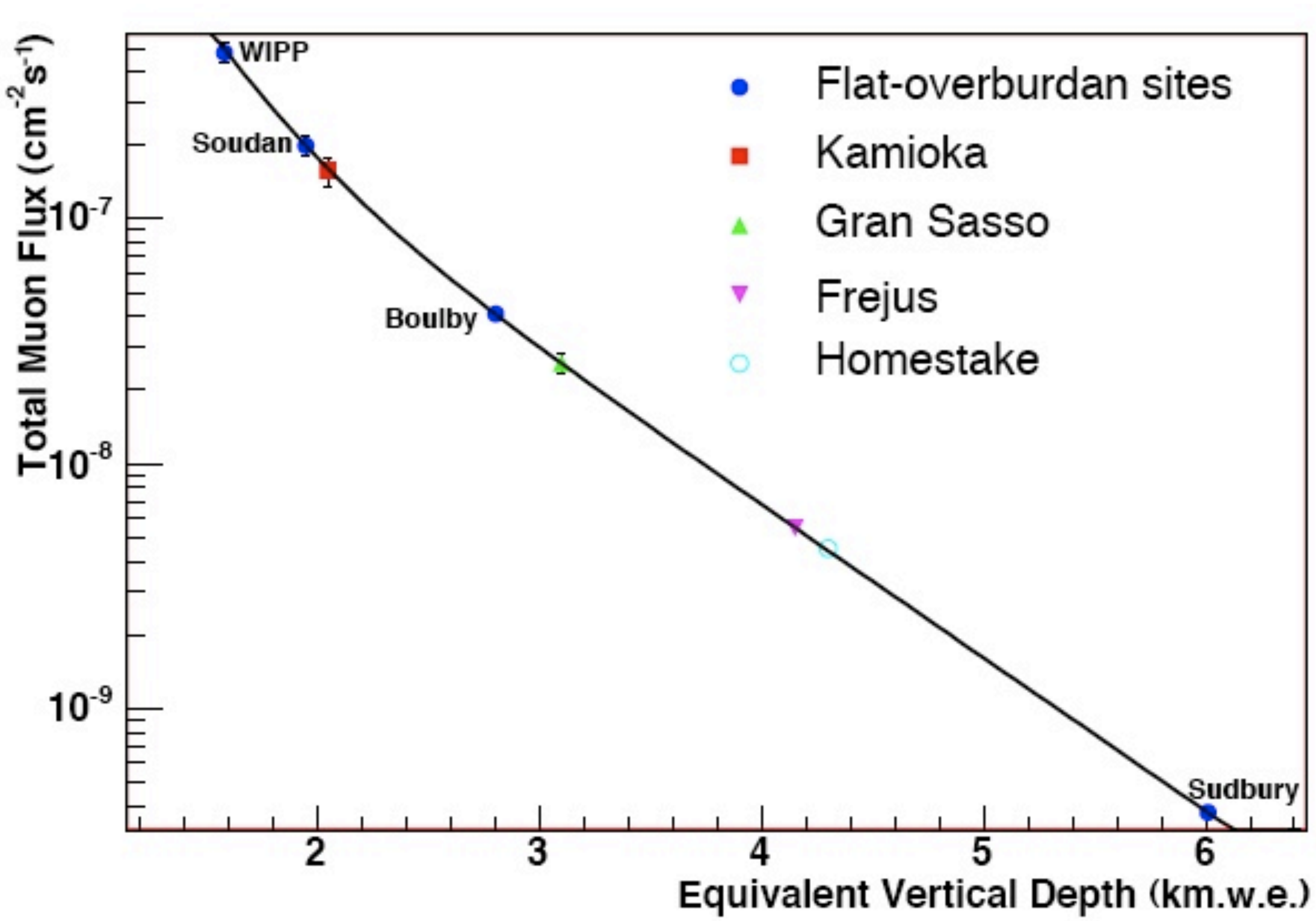
Messengers from the cosmos...



- High energy particles (mostly protons) from galactic and extra-galactic sources bombard our Earth's upper atmosphere.
- They interact with nuclei in the atmosphere (nitrogen, oxygen...) and create a shower of other particles.
- A significant fraction of these secondary particles are muons, a heavier cousin of electrons.

Shielding from cosmic rays?

- Higher elevation → higher exposure to cosmic rays
- To reduce cosmic ray exposure, go underground. In fact, all solar neutrino experiments (remember Ray Davis and his tank of cleaning fluid?) were installed in underground laboratories.



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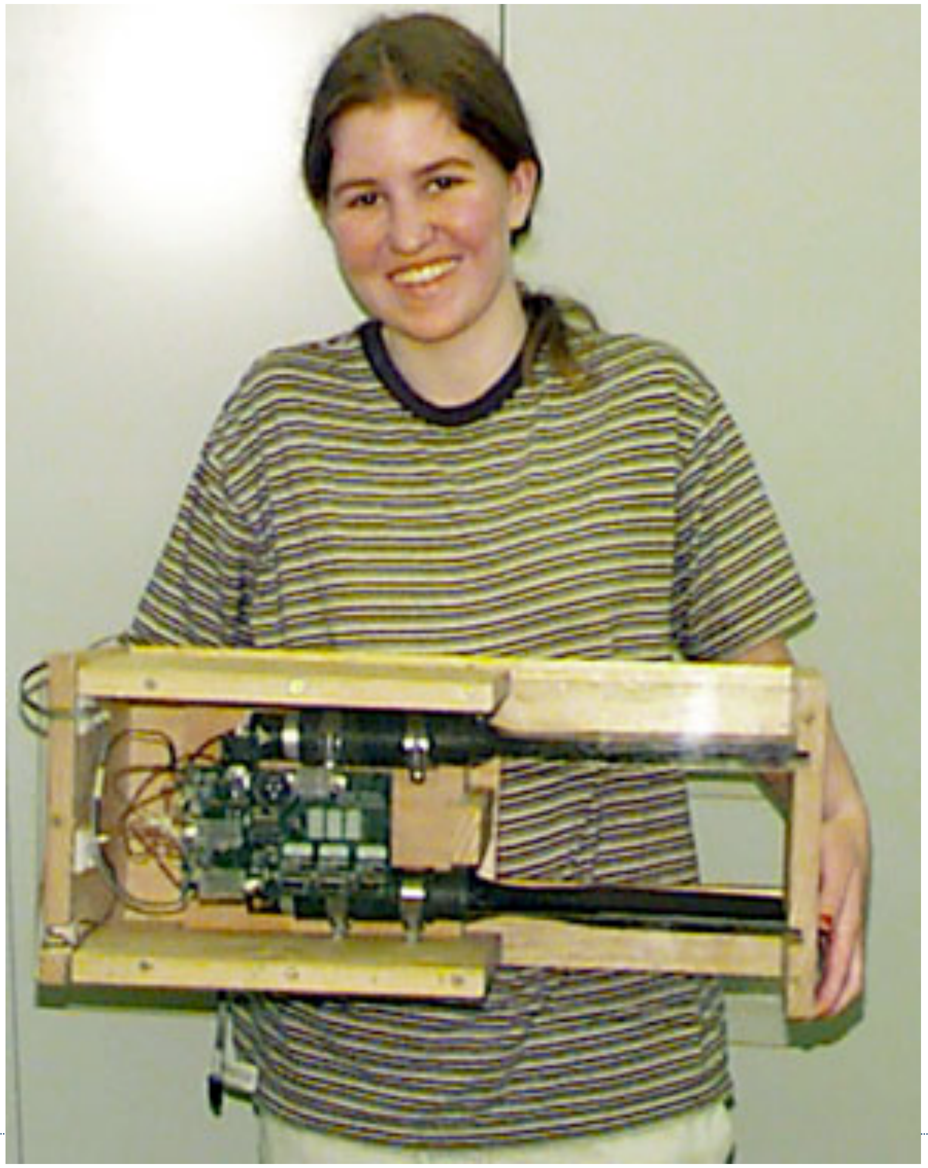
Cosmic rays

or you can take a detector up on a mountain...



The Cosmic Connection

http://www.lbl.gov/abc/cosmic/

Gabriel Poon - 8 years old

Thank you!